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(54) **Improvements in or relating to plasma reactors**

(57) A plasma reactor has a chamber (50) for containing a plasma and a passageway (60) communicating with the chamber is enhanced with a first removable plasma confinement magnet module placed adjacent the passageway including a first module housing (20,10) and a first plasma confinement magnet (80) inside the housing. It may further include a second removable plasma confinement magnet module placed adjacent the passageway including a second module housing (20,20), and a second plasma confinement magnet (82). Preferably, the first and second modules are located on opposite sides of the passageway. Moreover, the first and second plasma confinement magnets have magnetic orientations which tend to oppose plasma transport or leakage through the passageway. Preferably, the module housing includes a relatively non-magnetic thermal conductor such as aluminum and is in thermal contact with said chamber body. Cooling apparatus can be thermally coupled to the chamber body, whereby to maintain the first plasma confinement magnet below its Curie temperature. If the reactor includes a pumping annulus adjacent to a periphery of the chamber, then the passageway can be one which communicates between the chamber and the pumping annulus. Also, the passageway can be a wafer slit valve or a gas feed inlet. Such a gas feed inlet can be a center gas feed through a ceiling of the chamber. The module housing (20,20) can rest upon the chamber side wall and the chamber ceiling (52) can rest upon the module housing.
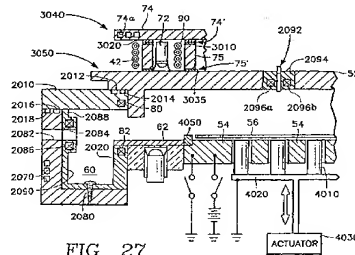
FIG. 27

Description

The invention is related to heating and cooling apparatus in an inductively coupled RF plasma reactors of the type having a reactor chamber ceiling overlying a workpiece being processed and an inductive coil antenna adjacent the ceiling.

EP-A-0837489 discloses thermal control apparatus for inductively coupled RF plasma reactor having an overhead solenoidal antenna and EP-A-0807952 discloses plasma with heated source of a polymer-hardening precursor material to which reference should be made.

In a plasma processing chamber, and especially in a high density plasma processing chamber, RF (radio frequency) power is used to generate and maintain a plasma within the processing chamber. As disclosed in detail in the above-referenced applications, it is often necessary to control temperatures of surfaces within the process chamber, independent of time varying heat loads imposed by processing conditions, or of other time varying boundary conditions. In some cases where the window/electrode is a semiconducting material, it may be necessary to control the temperature of the window/electrode within a temperature range to obtain the proper electrical properties of-the window. Namely, for the window/electrode to function simultaneously as a window and as an electrode, the electrical resistivity is a function of temperature for semiconductors, and the temperature of the window/electrode is best operated within a range of temperatures. The application of RF power to generate and maintain the plasma leads to heating of surfaces within the chamber, including windows (such as used for inductive or electromagnetic coupling of RF or microwave power) or electrodes (such as used for capacitive or electrostatic coupling of RF power, or for terminating or providing a ground or return path for such capacitive or electrostatic coupling of RF power) or for combination window/electrodes. Heating of those surfaces can occur due to 1) ion or electron bombardment, 2) absorption of light emitted from excited species, 3) absorption of power directly from the electromagnetic or electrostatic field, 4) radiation from other surfaces within the chamber, 5) conduction (typically small effect at low neutral gas pressure), 6) convection (typically small effect at low mass flow rates), 7) chemical reaction (i.e. at the surface of the window or electrode due to reaction with active species in plasma).

Depending on the process being performed with the plasma process chamber, it may be necessary to heat the window or electrode to a temperature above that temperature which the window or electrode would reach due to internal sources of heat as described above, or it may be necessary to cool the window or electrode to a temperature below that temperature which the window or electrode would reach due to internal sources of heat during some other portion of the operating process or sequence of processes. In such cases, a method for coupling heat into the window or electrode and a method for coupling heat out of the window or electrode is required.

Approaches for heating window/electrodes from outside the process chamber include the following:

1. heating the window/electrode by an external source of radiation (i.e., a lamp or radiant heater, or an inductive heat source),

2. heating the window/electrode by an external source of convection (i.e. forced fluid, heated by radiation, conduction, or convection),

3. heating the window/electrode by an external source of conduction (i.e., a resistive heater).

The foregoing heating methods, without any means for cooling, limit the temperature range available for window or electrode operation to temperatures greater than the temperature which the window or electrode would reach due to internal sources of heat alone.

Approaches for cooling window/electrodes from outside the process chamber include the following:

1. cooling the window/electrode by radiation to a colder external surface,

2. cooling the window/electrode by an external source of convection (i.e., natural or forced),

3. cooling the window/electrode by conduction to an external heat sink.

The foregoing cooling methods, without any means for heating other than internal heat sources, limit the temperature range available for window or electrode operation to temperatures less than that temperature which the window or electrode would reach due to internal sources of heat alone.

Additionally the foregoing cooling methods have the following problems:

1. cooling the window/electrode by radiation is limited to low heat transfer rates (which in many cases are insufficient for the window or electrode temperature range required and the rate of internal heating of window or electrodes) at low temperatures due to the T^4 dependence of radiation power, where T is the absolute (Kelvin) temperature of the surface radiating or absorbing heat;

2. cooling the window/electrode by an external source of convection can provide large heat transfer rates by using

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a liquid with high thermal conductivity, and high product of density & specific heat when high flow rates are used, but liquid convection cooling has the following problems:

A) it is limited to maximum temperature of operation by vapor pressure dependence of liquid on temperature (i.e. boiling point) (unless a phase change is allowed, which has its own problems - i.e. fixed temperature of phase change - no control range, as well safety issues),

B) incompatibility of liquid cooling with the electrical environment, depending upon liquid electrical properties, C) general integration issues with liquid in contact with reactor structural elements. Cooling the window or electrode by an external source of convection (e.g., a cooling gas) is limited to low heat transfer rates which in many cases are insufficient for the window or electrode temperature range required and the rate of internal heating of window or electrodes;

3. cooling the window/electrode by conduction to an external heat sink can provide high rates of heat transfer if the contact resistance between the window or electrode and the heat sink is sufficiently low, but low contact resistance is difficult to attain in practice.

Approaches for both heating and cooling window/electrodes from outside the process chamber include heating the window/electrode by an external source of conduction (i.e., a resistive heater) in combination with cooling the window/electrode by conduction to an external heat sink. In one implementation, the structure is as follows: a window or electrode has a heater plate (a plate with an embedded resistive heater) adjacent an outer surface of the window electrode. Additionally, a heat sink (typically liquid cooled) is placed proximate the opposite side of the heater plate from the window or electrode. Contact resistances are present between window or electrode and heater plate, and between the heater plate and the heat sink. In such a system integrated with automatic control of window or electrode temperature, a temperature measurement is made (continuously or periodically) of the window or electrode to be controlled, the temperature measurement is compared with a set point temperature, and based on the difference between the measured and set point temperatures a controller determines through a control algorithm how much power to apply to the resistive heater, or alternatively, how much cooling to apply to the heat sink, and the controller commands output transducers to output the determined heating or cooling levels. The process is repeated (continuously or periodically) until some desired degree of convergence of the window or electrode temperature to the set point temperature has occurs, and the control system remains active ready to respond to changes in requirements of heating or cooling levels due to changes in internal heat or cooling levels or to changes in the set point temperature. Besides contact resistance problems that limit the cooling capability of the system to control the temperature of the window or electrode, the system exhibits a time lag in transferring heat from the window or electrode to the head sink as required when the internal heating or cooling load changes during plasma reactor operation. This is due in part to the contact resistance between the window or electrode and the heater, and contact resistance between the heater and the heat sink, as well as the thermal capacitance of the heater and the window or electrode. For example, as the internal heat load is increased in a process or sequence of processes, the system senses the increase by measuring an increase in window or electrode temperature. As described above, the system reduces the heater power or increases the cooling power in response to the increase in window or electrode temperature, but there is a lag time for the heat to diffuse through the window or electrode, across the contact resistance between window or electrode and heater, through the heater plate, across the contact resistance between the heater and heat sink. In addition, "excess" heat energy "stored" in the heater diffuses across the contact resistance between the heater and heat sink. This lag causes more difficulty in controlling the temperature of the window or electrode as the internal heat or cooling load changes, typically resulting in some oscillation of the window or electrode temperature about the set point.

A further problem for a window or window/electrode (of the type that allows electromagnetic or inductive RF or microwave power to be coupled from outside the chamber to inside the chamber via the window or window/electrode) is that the presence of heat transfer apparatus (heater and/or heat sinks) interferes with the coupling of such electromagnetic or inductive RF or microwave power, and/or the presence of RF or microwave power coupling apparatus may interfere with heat transfer between heater and/or heat sink and window or window/electrode.

Thus a method is sought for heating and/or cooling a window or electrode or window electrode used in a plasma processing chamber so that the temperature of the window or electrode or window/electrode may be controlled sufficiently close to a set point such that a desired process or sequence of processes may be carried out within the plasma process chamber, independent of the change of internal heating or cooling loads within the chamber or changes in other boundary conditions.

Additionally, a method is sought for heating and/or cooling a window or window/electrode used in a plasma processing chamber so that the temperature of the window or electrode or window/electrode may be controlled sufficiently close to a set point temperature, without interference to coupling of electromagnetic or inductive RF or microwave power through the window or window/electrode such that a desired process or sequence of processes may be carried

out within the plasma process chamber, independent of the change of internal heating or cooling loads within the chamber or changes in other boundary conditions.

Additionally, a method is sought for heating and/or cooling an electrode or window/electrode used in a plasma processing chamber so that the temperature of the electrode or window/electrode may be controlled sufficiently close to a set point temperature, without interfering with capacitive or electrostatic coupling of RF power, or interfering with terminating or providing a ground or return path for such capacitive or electrostatic coupling of RF power, such that a desired process or sequence of processes may be carried out within the plasma process chamber, independent of the change of internal heating or cooling loads within the chamber or changes in other boundary conditions.

Additionally, a method is sought for heating and/or cooling a window or electrode or window/electrode used in a plasma processing chamber so that the temperature of the electrode or window/electrode may be controlled sufficiently close to a set point temperature, without interfering with capacitive or electrostatic coupling of RF power, or interfering with terminating or providing a ground or return path for such capacitive or electrostatic coupling RF power, and without interfering with coupling of electromagnetic or inductive RF or microwave power through the window or window/electrode such that a desired process or sequence of processes may be carried out within the plasma process chamber, independent of the change of internal heating or cooling loads within the chamber or changes in other boundary conditions.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention, a plasma reactor having a chamber for containing a plasma and a passageway communicating with the chamber is enhanced with a first removable plasma confinement magnet liner module placed adjacent the passageway including a first module housing and a first plasma confinement magnet inside the housing. It may further include a second removable plasma confinement magnet liner module placed adjacent the passageway including a second module housing, and a second plasma confinement magnet. Preferably, the first and second modules are located on opposite sides of the passageway. Moreover, the first and second plasma confinement magnets have magnetic orientations which tend to oppose plasma transport or leakage through the passageway. Preferably, the module housing includes a relatively non-magnetic thermal conductor such as aluminum and is in thermal contact with said chamber body. Cooling apparatus can be thermally coupled to the chamber body, whereby to maintain the first plasma confinement magnet below its Curie temperature. If the reactor includes a pumping annulus adjacent of a periphery of the chamber, then the passageway can be one which communicates between the chamber and the pumping annulus. Also, the passageway can be a wafer slit valve or a gas feed inlet. Such a gas feed inlet can be a center gas feed through a ceiling of the chamber. The module housing can rest upon the chamber side wall and the chamber ceiling can rest upon the module housing.

Preferably, the module housing includes an opening, the first magnet being located inside the opening, the module housing further including a bonding layer attaching the first magnet to an interior surface inside the opening and a cover plate covering the opening so as to seal the first magnet inside the first module housing. A welding bond is preferably formed between the cover plate and the first module housing by E-beam welding, laser welding or the like.

In accordance with a second aspect of the invention, a plasma reactor including a reactor chamber enclosure including a ceiling, plural semiconductor cooling rings resting on top of the ceiling and a cold plate overlying the plural semiconductor cooling rings is enhanced with an elastically deformable thermally conductive layer between each one of the plural semiconductor cooling rings and the cold plate, such as Grafoil. In addition, an RF reflector coating may be placed between the elastically deformable thermally conductive layer and the cooling plate. The RF reflector coating preferably is thermally conductive and electrically conductive and may be aluminum and prevents shunting of RF power to the cooling plate.

In accordance with a third aspect of the invention, a plasma reactor includes a reactor chamber, an electrostatic chuck for supporting a workpiece inside the chamber, and plural semiconductor grounding pins extending through the electrostatic chuck toward a plane whereon the chuck is capable of supporting the workpiece, the pins being movable between an extended position at which the pins can contact the workpiece and a retracted position. It can further include a frame supporting the pins, the frame being connectable to a ground potential and an actuator for moving the frame whereby to transport the pins between the extended and retracted positions. The pins can be silicon or silicon carbide, for example.

In accordance with a further aspect of the invention, a semiconductor collar may be formed around a periphery of the electrostatic chuck. The semiconductor collar can be silicon carbide which may be formed by chemical vapor deposition on the periphery of the electrostatic chuck. In addition, the reactor may further including a heated semiconductor ring surrounding the electrostatic chuck. The heated semiconductor ring may have a radial slit to permit thermal expansion of the heated semiconductor ring.

In accordance with a yet further aspect of the invention, a plasma reactor includes an inductive antenna including plural stacked coil windings, each of the coil windings residing generally in a respective one of plural parallel planes,

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the windings in adjacent planes being connected at a step region common to all the planes wherein each winding transitions from one plane to the next plane, the coil windings being formed of a single conductor having a pair of connection sections, a first one of the connection sections extending from a top-most one of the windings and a second one of the ends extending from a bottom-most one of the windings, the first connection section extending upwardly away from the top-most winding, the second connection section following an arcuate path upwardly from the bottom-most winding to the top-most winding so as to provide an effective number of stacked windings which is generally uniform along the step region.

The following is a description of some specific embodiments of the invention, reference being made to the accompanying drawings, in which:

FIG. 1 is a cut-away side view of an inductively coupled plasma reactor of the type employed in a co-pending U. S. patent application referred to above employing generally planar coil antennas.

FIG. 2 is a log-log scale graph of induction field skin depth in a plasma in cm (solid line) and of electron-to-neutral elastic collision mean free path length (dashed line) as functions of pressure in torr (horizontal axis).

FIG. 3A is a graph of plasma ion density as a function of radial position relative to the workpiece center in the reactor of FIG. 1 for a workpiece-to-ceiling height of 4 inches, the curves labelled A and B corresponding to plasma ion densities produced by outer and inner coil antennas respectively.

FIG. 3B is a graph of plasma ion density as a function of radial position relative to the workpiece center in the reactor of FIG. 1 for a workpiece-to-ceiling height of 3 inches, the curves labelled A and B corresponding to plasma ion densities produced by outer and inner coil antennas respectively.

FIG. 3C is a graph of plasma ion density as a function of radial position relative to the workpiece center in the reactor of FIG. 1 for a workpiece-to-ceiling height of 2.5 inches, the curves labelled A and B corresponding to plasma ion densities produced by outer and inner coil antennas respectively.

FIG. 3D is a graph of plasma ion density as a function of radial position relative to the workpiece center in the reactor of FIG. 1 for a workpiece-to-ceiling height of 1.25 inches, the curves labelled A and B corresponding to plasma ion densities produced by outer and inner coil antennas respectively.

FIG. 3E is a graph of plasma ion density as a function of radial position relative to the workpiece center in the reactor of FIG. 1 for a workpiece-to-ceiling height of 0.8 inches, the curves labelled A and B corresponding to plasma ion densities produced by outer and inner coil antennas respectively.

FIG. 4A is a cut-away side view of a plasma reactor employing a single three-dimensional center non-planar solenoid winding.

FIG. 4B is an enlarged view of a portion of the reactor of FIG. 4A illustrating a preferred way of winding the solenoidal winding.

FIG. 4C is a cut-away side view of a plasma reactor corresponding to FIG. 4A but having a dome-shaped ceiling.

FIG. 4D is a cut-away side view of a plasma reactor corresponding to FIG. 4A but having a conical ceiling.

FIG. 4E is a cut-away side view of a plasma reactor corresponding to FIG. 4D but having a truncated conical ceiling.

FIG. 5 is a cut-away side view of a plasma reactor employing inner and outer vertical solenoid windings.

FIG. 6 is a cut-away side view of a plasma reactor corresponding to FIG. 5 in which the outer winding is flat.

FIG. 7A is a cut-away side view of a plasma reactor corresponding to FIG. 4 in which the center solenoid winding consists of plural upright cylindrical windings.

FIG. 7B is a detailed view of a first implementation of the embodiment of FIG. 7A.

FIG. 7C is a detailed view of a second implementation of the embodiment of FIG. 7A.

FIG. 8 is a cut-away side view of a plasma reactor corresponding to FIG. 5 in which both the inner and outer windings consist of plural upright cylindrical windings.

FIG. 9 is a cut-away side view of a plasma reactor corresponding to FIG. 5 in which the inner winding consists of plural upright cylindrical windings and the outer winding consists of a single upright cylindrical winding.

FIG. 10 is a cut-away side view of a plasma reactor in which a single solenoid winding is placed at an optimum radial position for maximum plasma ion density uniformity.

FIG. 11 is a cut-away side view of a plasma reactor corresponding to FIG. 4 in which the solenoid winding is an inverted conical shape.

FIG. 12 is a cut-away side view of a plasma reactor corresponding to FIG. 4 in which the solenoid winding is an upright conical shape.

FIG. 13 is a cut-away side view of a plasma reactor in which the solenoid winding consists of an inner upright cylindrical portion and an outer flat portion.

FIG. 14 is a cut-away side view of a plasma reactor corresponding to FIG. 10 in which the solenoid winding includes both an inverted conical portion and a flat portion.

FIG. 15 is a cut-away side view of a plasma reactor corresponding to FIG. 12 in which the solenoid winding includes both an upright conical portion and a flat portion.

FIG. 16 illustrates a combination of planar, conical and dome-shaped ceiling elements.

FIG. 17A illustrates a separately biased silicon side wall and ceiling and employing electrical heaters.

FIG. 17B illustrates separately biased inner and outer silicon ceiling portions and employing electrical heaters.

FIG. 18 is a cut-away cross-sectional view illustrating a first embodiment of the plasma reactor having a thermally conductive gas interface at each face of the thermally conductive torus of FIG. 5.

FIG. 19 is a cut-away cross-sectional view illustrating a second embodiment of the plasma reactor having a thermally conductive gas interface at the one face of a thermally conductive torus integrally formed with the semiconductor window electrode.

FIG. 20 is a cut-away cross-sectional view illustrating a third embodiment of the plasma reactor having a thermally conductive solid interface material at each face of the thermally conductive torus of FIG. 5.

FIG. 21 is a cut-away cross-sectional view illustrating a fourth embodiment of the plasma reactor having a thermally conductive solid interface material at the one face of a thermally conductive torus integrally formed with the semiconductor window electrode.

FIG. 22 is a cut-away cross-sectional view illustrating a fifth embodiment of the plasma reactor in which the disposable silicon-containing ring of FIG. 5 is cooled by a cold plate with a thermally conductive gas interface between the cold plate and the disposable silicon ring.

FIG. 23 is a cut-away cross-sectional view illustrating a sixth embodiment of the plasma reactor in which the disposable silicon-containing ring of FIG. 5 is cooled by a cold plate with a thermally conductive solid interface material between the cold plate and the disposable silicon ring.

FIG. 24 illustrates a seventh embodiment of the plasma reactor in which the chamber wall and an interior chamber liner are cooled using a thermally conductive gas in the interfaces across the heat conduction paths.

FIG. 25 illustrates a modification of the embodiment of FIG. 24 in which the interfaces are each filled with a solid thermally conductive layer instead of the thermally conductive gas.

FIG. 26 illustrates the embodiment of FIG. 22 in which the ring is electrostatically clamped to seal the thermally conductive gas.

FIG. 27 illustrates a plasma reactor embodying different aspects of the plasma reactor including modular plasma confinement magnet liners.

FIG. 28 is an enlarged view of a portion of a modular plasma confinement magnet liner, illustrating how a magnet is sealed within the liner.

FIG. 29 illustrates a heated silicon ring employed in the reactor of FIG. 27 having a slit therethrough to permit thermal expansion.

FIG. 30 illustrates an inductive antenna employed in the reactor of FIG. 27 having a uniform number of effective windings around its azimuth.

FIGS. 31A-31E illustrates different magnetic orientations for pairs of plasma confinement magnets employed in the reactor of FIG. 27.

In a plasma reactor having a small antenna-to-workpiece gap, in order to minimize the decrease in plasma ion density near the center region of the workpiece corresponding to the inductive antenna pattern center null, it is an object of the invention to increase the magnitude of the induced electric field at the center region. The invention accomplishes this by concentrating the turns of an inductive coil overlying the ceiling near the axis of symmetry of the antenna and maximizing the rate of change (at the RF source frequency) of magnetic flux linkage between the antenna and the plasma in that center region.

In accordance with the invention, a solenoidal coil around the symmetry axis simultaneously concentrates its inductive coil turns near the axis and maximizes the rate of change of magnetic flux linkage between the antenna and the plasma in the center region adjacent the workpiece. This is because the number of turns is large and the coil radius is small, as required for strong flux linkage and close mutual coupling to the plasma in the center region. (In contrast, a conventional planar coil antenna spreads its inductive field over a wide radial area, pushing the radial power distribution outward toward the periphery.) As understood in this specification, a solenoid-like antenna is one which has plural inductive elements distributed in a non-planar manner relative to a plane of the workpiece or workpiece support surface or overlying chamber ceiling, or spaced at different distances transversely to the workpiece support plane (defined by a workpiece supporting pedestal within the chamber) or spaced at different distances transversely to an overlying chamber ceiling. As understood in this specification, an inductive element is a current-carrying element mutually inductively coupled with the plasma in the chamber and/or with other inductive elements of the antenna.

A preferred embodiment of the invention includes dual solenoidal coil antennas with one solenoid near the center and another one at an outer peripheral radius. The two solenoids may be driven at different RF frequencies or at the same frequency, in which case they are preferably phase-locked and more preferably phase-locked in such a manner that their fields constructively interact. The greatest practical displacement between the inner and outer solenoid is preferred because it provides the most versatile control of etch rate at the workpiece center relative to etch rate at the workpiece periphery. The skilled worker may readily vary RF power, chamber pressure and electro-negativity of the process gas mixture (by choosing the appropriate ratio of molecular and inert gases) to obtain a wider range or process

window in which to optimize (using the plasma reactor) the radial uniformity of the etch rate across the workpiece. Maximum spacing between the separate inner and outer solenoids of the preferred embodiment provides the following advantages:

5   (1) maximum uniformity control and adjustment;
       (2) maximum isolation between the inner and outer solenoids, preventing interference of the field from one solenoid with that of the other; and
       (3) maximum space on the ceiling (between the inner and outer solenoids) for temperature control elements to optimize ceiling temperature control.

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FIG. 4A illustrates a single solenoid embodiment (not the preferred embodiment) of an inductively coupled RF plasma reactor having a short workpiece-to-ceiling gap, meaning that the skin depth of the induction field is on the order of the gap length. As understood in this specification, a skin depth which is on the order of the gap length is that which is within a factor of ten of (i.e., between about one tenth and about ten times) the gap length.

15   FIG. 5 illustrates a dual solenoid embodiment of an inductively coupled RF plasma reactor, and is the preferred embodiment of the invention. Except for the dual solenoid feature, the reactor structure of the embodiments of FIGS. 4A and 5 is nearly the same, and will now be described with reference to FIG. 4A. The reactor includes a cylindrical chamber 40 similar to that of FIG. 1, except that the reactor of FIG. 4A has a non-planar coil antenna 42 whose windings 44 are closely concentrated in non-planar fashion near the antenna symmetry axis 46. While in the illustrated embod-

20   iment the windings 44 are symmetrical and their symmetry axis 46 coincides with the center axis of the chamber, the invention may be carried out differently. For example, the windings may not be symmetrical and/or their axis of symmetry may not coincide. However, in the case of a symmetrical antenna, the antenna has a radiation pattern null near its symmetry axis 46 coinciding with the center of the chamber or the workpiece center. Close concentration of the windings 44 about the center axis 46 compensates for this null and is accomplished by vertically stacking the windings 44 in the

25   manner of a solenoid so that they are each a minimum distance from the chamber center axis 46. This increases the product of current (I) and coil turns (N) near the chamber center axis 46 where the plasma ion density has been the weakest for short workpiece-to-ceiling heights, as discussed above with reference to FIGS. 3D and 3E. As a result, the RF power applied to the non-planar coil antenna 42 produces greater induction [d/dt][N•I] at the wafer center --at the antenna symmetry axis 46-- (relative to the peripheral regions) and therefore produces greater plasma ion density

30   in that region, so that the resulting plasma ion density is more nearly uniform despite the small workpiece-to-ceiling height. Thus, the invention provides a way for reducing the ceiling height for enhanced plasma process performance without sacrificing process uniformity.

The drawing of FIG. 4B best shows a preferred implementation of the windings employed in the embodiments of FIGS. 4A and 5. In order that the windings 44 be at least nearly parallel to the plane of the workpiece 56, they preferably

35   are not wound in the usual manner of a helix but, instead, are preferably wound so that each individual turn is parallel to the (horizontal) plane of the workpiece 56 except at a step or transition 44a between turns (from one horizontal plane to the next).

The cylindrical chamber 40 consists of a cylindrical side wall 50 and a circular ceiling 52 integrally formed with the side wall 50 so that the side wall 50 and ceiling 52 constitute a single piece of material, such as silicon. However, the

40   invention may be carried out with the side wall 50 and ceiling 52 formed as separate pieces, as will be described later in this specification. The circular ceiling 52 may be of any suitable cross-sectional shape such as planar (FIG. 4A), dome (FIG. 4C), conical (FIG. 4D), truncated conical (FIG. 4E), cylindrical or any combination of such shapes or curve of rotation. Such a combination will be discussed later in this specification. Generally, the vertical pitch of the solenoid 42 (i.e., its vertical height divided by its horizontal width) exceeds the vertical pitch of the ceiling 52, even for ceilings

45   defining 3-dimensional surfaces such as dome, conical, truncated conical and so forth. The purpose for this, at least in the preferred embodiment, is to concentrate the induction of the antenna near the antenna symmetry axis, as discussed previously in this specification. A solenoid having a pitch exceeding that of the ceiling is referred to herein as a non-conformal solenoid, meaning that, in general, its shape does not conform with the shape of the ceiling, and more specifically that its vertical pitch exceeds the vertical pitch of the ceiling. A 2-dimensional or flat ceiling has a vertical

50   pitch of zero, while a 3-dimensional ceiling has a non-zero vertical pitch.

A pedestal 54 at the bottom of the chamber 40 supports a planar workpiece 56 in a workpiece support plane during processing. The workpiece 56 is typically a semiconductor wafer and the workpiece support plane is generally the plane of the wafer or workpiece 56. The chamber 40 is evacuated by a pump (not shown in the drawing) through an annular passage 58 to a pumping annulus 60 surrounding the lower portion of the chamber 40. The interior of the

55   pumping annulus may be lined with a replaceable metal liner 60a. The annular passage 58 is defined by the bottom edge 50a of the cylindrical side wall 50 and a planar ring 62 surrounding the pedestal 54. Process gas is furnished into the chamber 40 through any one or all of a variety of gas feeds. In order to control process gas flow near the workpiece center, a center gas feed 64a can extend downwardly through the center of the ceiling 52 toward the center of the

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workpiece 56 (or the center of the workpiece support plane). In order to control gas flow near the workpiece periphery (or near the periphery of the workpiece support plane), plural radial gas feeds 64b, which can be controlled independently of the center gas feed 64a, extend radially inwardly from the side wall 50 toward the workpiece periphery (or toward the workpiece support plane periphery), or base axial gas feeds 64c extend upwardly from near the pedestal
5   54 toward the workpiece periphery, or ceiling axial gas feeds 64d can extend downwardly from the ceiling 52 toward the workpiece periphery. Etch rates at the workpiece center and periphery can be adjusted independently relative to one another to achieve a more radially uniform etch rate distribution across the workpiece by controlling the process gas flow rates toward the workpiece center and periphery through, respectively, the center gas feed 64a and any one of the outer gas feeds 64b-d. This feature of the invention can be carried out with the center gas feed 64a and only
10   one of the peripheral gas feeds 64b-d.

The solenoidal coil antenna 42 is wound around a housing 66 surrounding the center gas feed 64. A plasma source RF power supply 68 is connected across the coil antenna 42 and a bias RF power supply 70 is connected to the pedestal 54.

Confinement of the overhead coil antenna 42 to the center region of the ceiling 52 leaves a large portion of the
15   top surface of the ceiling 52 unoccupied and therefore available for direct contact with temperature control apparatus including, for example, plural radiant heaters 72 such as tungsten halogen lamps and a water-cooled cold plate 74 which may be formed of copper or aluminum for example, with coolant passages 74a extending therethrough. Preferably the coolant passages 74a contain a coolant of a known variety having a high thermal conductivity but a low electrical conductivity, to avoid electrically loading down the antenna or solenoid 42. The cold plate 74 provides constant
20   cooling of the ceiling 52 while the maximum power of the radiant heaters 72 is selected so as to be able to overwhelm, if necessary, the cooling by the cold plate 74, facilitating responsive and stable temperature control of the ceiling 52. The large ceiling area irradiated by the heaters 72 provides greater uniformity and efficiency of temperature control. (It should be noted that radiant heating is not necessarily required in carrying out the invention, and the skilled worker may choose to employ an electric heating element instead, as will be described later in this specification.) If the ceiling
25   52 is silicon, as disclosed in co-pending U.S. application Serial No. 08/597,577 filed February 2, 1996 by Kenneth S. Collins et al., then there is a significant advantage to be gained by thus increasing the uniformity and efficiency of the temperature control across the ceiling. Specifically, where a polymer precursor and etchant precursor process gas (e. g., a fluorocarbon gas) is employed and where it is desirable to scavenge the etchant (e.g., fluorine), the rate of polymer deposition across the entire ceiling 52 and/or the rate at which the ceiling 52 furnishes a fluorine etchant scavenger
30   material (silicon) into the plasma is better controlled by increasing the contact area of the ceiling 52 with the temperature control heater 72. The solenoid antenna 42 increases the available contact area on the ceiling 52 because the solenoid windings 44 are concentrated at the center axis of the ceiling 52.

The increase in available area on the ceiling 52 for thermal contact is exploited in a preferred implementation by a highly thermally conductive torus 75 (formed of a ceramic such as aluminum nitride, aluminum oxide or silicon nitride
35   or of a non-ceramic like silicon or silicon carbide either lightly doped or undoped) whose bottom surface rests on the ceiling 52 and whose top surface supports the cold plate 74. One feature of the torus 75 is that it displaces the cold plate 74 well-above the top of the solenoid 42. This feature substantially mitigates or nearly eliminates the reduction in inductive coupling between the solenoid 42 and the plasma which would otherwise result from a close proximity of the conductive plane of the cold plate 74 to the solenoid 42. In order to prevent such a reduction in inductive coupling,
40   it is preferable that the distance between the cold plate 74 and the top winding of the solenoid 42 be at least a substantial fraction (e.g., one half) of the total height of the solenoid 42. Plural axial holes 75a extending through the torus 75 are spaced along two concentric circles and hold the plural radiant heaters or lamps 72 and permit them to directly irradiate the ceiling 52. For greatest lamp efficiency, the hole interior surface may be lined with a reflective (e.g., aluminum) layer. The center gas feed 64a of FIG. 4 may be replaced by a radiant heater 72 (as shown in FIG. 5), depending upon
45   the particular reactor design and process conditions. The ceiling temperature is sensed by a sensor such as a thermocouple 76 extending through one of the holes 75a not occupied by a lamp heater 72. For good thermal contact, a highly thermally conductive elastomer 73 such as silicone rubber impregnated with boron nitride- is placed between the ceramic torus 75 and the copper cold plate 74 and between the ceramic torus 75 and the silicon ceiling 52.

As disclosed in the above-referenced co-pending application, the chamber 40 may be an all-semiconductor cham-
50   ber, in which case the ceiling 52 and the side wall 50 are both a semiconductor material such as silicon or silicon carbide. As described in the above-referenced co-pending application, controlling the temperature of, and RF bias power applied to, either the ceiling 52 or the wall 50 regulates the extent to which it furnishes fluorine scavenger precursor material (silicon) into the plasma or, alternatively, the extent to which it is coated with polymer. The material of the ceiling 52 is not limited to silicon but may be, in the alternative, silicon carbide, silicon dioxide (quartz), silicon
55   nitride, aluminum nitride or a ceramic such as aluminum oxide.

As described in the above-referenced co-pending application, the chamber wall or ceiling 50, 52 need not be used as the source of a fluorine scavenger material. Instead, a disposable semiconductor (e.g., silicon or silicon carbide) member can be placed inside the chamber 40 and maintained at a sufficiently high temperature to prevent polymer

condensation thereon and permit silicon material to be removed therefrom into the plasma as fluorine scavenging material. In this case, the wall 50 and ceiling 52 need not necessarily be silicon, or if they are silicon they may be maintained at a temperature (and/or RF bias) near or below the polymer condensation temperature (and/or a polymer condensation RF bias threshold) so that they are coated with polymer from the plasma so as to be protected from

5 being consumed. While the disposable silicon member may take any appropriate form, in the embodiment of FIG. 4 the disposable silicon member is an annular ring 62 surrounding the pedestal 54. Preferably, the annular ring 62 is high purity silicon and may be doped to alter its electrical or optical properties. In order to maintain the silicon ring 62 at a sufficient temperature to ensure its favorable participation in the plasma process (e.g., its contribution of silicon material into the plasma for fluorine scavenging), plural radiant (e.g., tungsten halogen lamp) heaters 77 arranged in

10 a circle under the annular ring 62 heat the silicon ring 62 through a quartz window 78. As described in the above-referenced co-pending application, the heaters 77 are controlled in accordance with the measured temperature of the silicon ring 62 sensed by a temperature sensor 79 which may be a remote sensor such as an optical pyrometer or a fluoro-optical probe. The sensor 79 may extend partially into a very deep hole 62a in the ring 62, the deepness and narrowness of the hole tending at least partially to mask temperature-dependent variations in thermal emissivity of the

15 silicon ring 62, so that it behaves more like a gray-body radiator for more reliable temperature measurement.

As described in EP-A-0837489, referred to above, an advantage of an all-semiconductor chamber is that the plasma is free of contact with contaminant producing materials such as metal, for example. For this purpose, plasma confinement magnets 80, 82 adjacent the annular opening 58 prevent or reduce plasma flow into the pumping annulus 60. To the extent any polymer precursor and/or active species succeeds in entering the pumping annulus 60, any

20 resulting polymer or contaminant deposits on the replaceable interior liner 60a may be prevented from reentering the plasma chamber 40 by maintaining the liner 60a at a temperature significantly below the polymer condensation temperature, for example, as disclosed in the referenced co-pending application.

A wafer slit valve 84 through the exterior wall of the pumping annulus 60 accommodates wafer ingress and egress. The annular opening 58 between the chamber 40 and pumping annulus 60 is larger adjacent the wafer slit valve 84

25 and smallest on the opposite side by virtue of a slant of the bottom edge of the cylindrical side wall 50 so as to make the chamber pressure distribution more symmetrical with a non-symmetrical pump port location.

Maximum mutual inductance near the chamber center axis 46 is achieved by the vertically stacked solenoidal windings 44. In the embodiment of FIG. 4, another winding 45 outside of the vertical stack of windings 44 but in the horizontal plane of the bottom solenoidal winding 44a may be added, provided the additional winding 45 is close to

30 the bottom solenoidal winding 44a.

Referring specifically now to the preferred dual solenoid embodiment of FIG. 5, a second outer vertical stack or solenoid 120 of windings 122 at an outer location (i.e, against the outer circumferential surface of the thermally conductive torus 75) is displaced by a radial distance δR from the inner vertical stack of solenoidal windings 44. Note that in FIG. 5 confinement of the inner solenoidal antenna 42 to the center and the outer solenoidal antenna 120 to the

35 periphery leaves a large portion of the top surface of the ceiling 52 available for direct contact with the temperature control apparatus 72, 74, 75, as in FIG. 4A. An advantage is that the larger surface area contact between the ceiling 52 and the temperature control apparatus provides a more efficient and more uniform temperature control of the ceiling 52.

For a reactor in which the side wall and ceiling are formed of a single piece of silicon for example with an inside

40 diameter of 12.6 in (32 cm), the wafer-to-ceiling gap is 3 in (7.5 cm), and the mean diameter of the inner solenoid was 3.75 in (9.3 cm) while the mean diameter of the outer solenoid was 11.75 in (29.3 cm) using 3/16 in diameter hollow copper tubing covered with a 0.03 thick teflon insulation layer, each solenoid consisting of four turns and being 1 in (2.54 cm) high. The outer stack or solenoid 120 is energized by a second independently controllable plasma source RF power supply 96. The purpose is to permit different user-selectable plasma source power levels to be applied at

45 different radial locations relative to the workpiece or wafer 56 to permit compensation for known processing non-uniformities across the wafer surface, a significant advantage. In combination with the independently controllable center gas feed 64a and peripheral gas feeds 64b-d, etch performance at the workpiece center may be adjusted relative to etch performance at the edge by adjusting the RF power applied to the inner solenoid 42 relative to that applied to the outer solenoid 90 and adjusting the gas flow rate through the center gas feed 64a relative to the flow rate through the

50 outer gas feeds 64b-d. While the plasma reactor solves or at least ameliorates the problem of a center null or dip in the inductance field as described above, there may be other plasma processing non-uniformity problems, and these can be compensated in the versatile embodiment of FIG. 5 by adjusting the relative RF power levels applied to the inner and outer antennas. For effecting this purpose with greater convenience, the respective RF power supplies 68, 96 for the inner and outer solenoids 42, 90 may be replaced by a common power supply 97a and a power splitter 97b

55 which permits the user to change the relative apportionment of power between the inner and outer solenoids 42, 90 while preserving a fixed phase relationship between the fields of the inner and outer solenoids 42, 90. This is particularly important where the two solenoids 42, 90 receive RF power at the same frequency. Otherwise, if the two independent power supplies 68, 96 are employed, then they may be powered at different RF frequencies, in which case it is preferable

to install RF filters at the output of each RF power supply 68, 96 to avoid off-frequency feedback from coupling between the two solenoids. In this case, the frequency difference should be sufficient to time-average out coupling between the two solenoids and, furthermore, should exceed the rejection bandwidth of the RF filters. A preferred mode is to make each frequency independently resonantly matched to the respective solenoid, and each frequency may be varied to

5　follow changes in the plasma impedance (thereby maintaining resonance) in lieu of conventional impedance matching techniques. In other words, the RF frequency applied to the antenna is made to follow the resonant frequency of the antenna as loaded by the impedance of the plasma in the chamber. In such implementations, the frequency ranges of the two solenoids should be mutually exclusive. In an alternative mode, the two solenoids are driven at the same RF frequency and in this case it is preferable that the phase relationship between the two be such as to cause constructive

10　interaction or superposition of the fields of the two solenoids. Generally, this requirement will be met by a zero phase angle between the signals applied to the two solenoids if they are both wound in the same sense. Otherwise, if they are oppositely wound, the phase angle is preferably 180°. In any case, coupling between the inner and outer solenoids can be minimized or eliminated by having a relatively large space between the inner and outer solenoids 42, 90, as will be discussed below in this specification.

15　The range attainable by such adjustments is increased by increasing the radius of the outer solenoid 90 to increase the spacing between the inner and outer solenoids 42, 90, so that the effects of the two solenoids 42, 90 are more confined to the workpiece center and edge, respectively. This permits a greater range of control in superimposing the effects of the two solenoids 42, 90. For example, the radius of the inner solenoid 42 should be no greater than about half the workpiece radius and preferably no more than about a third thereof. (The minimum radius of the inner solenoid

20　42 is affected in part by the diameter of the conductor forming the solenoid 42 and in part by the need to provide a finite non-zero circumference for an arcuate --e.g., circular-- current path to produce inductance.) The radius of the outer coil 90 should be at least equal to the workpiece radius and preferably 1.5 or more times the workpiece radius. With such a configuration, the respective center and edge effects of the inner and outer solenoids 42, 90 are so pronounced that by increasing power to the inner solenoid the chamber pressure can be raised into the hundreds of mT

25　while providing a uniform plasma, and by increasing power to the outer solenoid 90 the chamber pressure can be reduced to on the order of 0.01 mT while providing a uniform plasma. Another advantage of such a large radius of the outer solenoid 90 is that it minimizes coupling between the inner and outer solenoids 42, 90.

FIG. 5 indicates in dashed line that a third solenoid may be added as an option, which is desirable for a very large chamber diameter.

30　FIG. 6 illustrates a variation of the embodiment of FIG. 5 in which the outer solenoid 90 is replaced by a planar winding 100.

FIG. 7A illustrates a variation of the embodiment of FIG. 4 in which the center solenoidal winding includes not only the vertical stack 42 of windings 44 but in addition a second vertical stack 102 of windings 104 closely adjacent to the first stack 42 so that the two stacks constitute a double-wound solenoid 106. Referring to FIG. 7B, the doubly wound

35　solenoid 106 may consist of two independently wound single solenoids 42, 102, the inner solenoid 42 consisting of the windings 44a, 44b, and so forth and the outer solenoid 102 consisting of the winding 104a, 104b and so forth. Alternatively, referring to FIG. 7C, the doubly wound solenoid 106 may consist of vertically stacked pairs of at least nearly co-planar windings. In the alternative of FIG. 7C, each pair of nearly co-planar windings (e.g., the pair 44a, 104a or the pair 44b, 104b) may be formed by helically winding a single conductor. The term "doubly wound" used herein

40　refers to winding of the type shown in either FIG. 7B or 7C. In addition, the solenoid winding may not be merely doubly wound but may be triply wound or more and in general it can consists of plural windings at each plane along the axis of symmetry. Such multiple-wound solenoids may be employed in either one or both the inner and outer solenoids 42, 90 of the dual-solenoid embodiment of FIG. 5.

FIG. 8 illustrates a variation of the embodiment of FIG. 7A in which an outer doubly wound solenoid 110 concentric

45　with the inner doubly wound solenoid 106 is placed at a radial distance δR from the inner solenoid 106.

FIG. 9 illustrates a variation of the embodiment of FIG. 8 in which the outer doubly wound solenoid 110 is replaced by an ordinary outer solenoid 112 corresponding to the outer solenoid employed in the embodiment of FIG. 5.

FIG. 10 illustrates another preferred embodiment in which the solenoid 42 of FIG. 5 is placed at a location displaced by a radial distance δr from the center gas feed housing 66. In the embodiment of FIG. 4, δr is zero while in the

50　embodiment of FIG. 10 δr is a significant fraction of the radius of the cylindrical side wall 50. Increasing δr to the extent illustrated in FIG. 10 may be helpful as an alternative to the embodiments of FIGS. 4, 5, 7 and 8 for compensating for non-uniformities in addition to the usual center dip in plasma ion density described with reference to FIGS. 3D and 3E. Similarly, the embodiment of FIG. 10 may be helpful where placing the solenoid 42 at the minimum distance from the chamber center axis 46 (as in FIG. 4) would so increase the plasma ion density near the center of the wafer 56 as to

55　over-correct for the usual dip in plasma ion density near the center and create yet another non-uniformity in the plasma process behavior. In such a case, the embodiment of FIG. 10 is preferred where δr is selected to be an optimum value which provides the greatest uniformity in plasma ion density. Ideally in this case, δr is selected to avoid both undercorrection and over-correction for the usual center dip in plasma ion density. The determination of the optimum value

for δr can be carried out by the skilled worker by trial and error steps of placing the solenoid 42 at different radial locations and employing conventional techniques to determine the radial profile of the plasma ion density at each step.

FIG. 11 illustrates an embodiment in which the solenoid 42 has an inverted conical shape while FIG. 12 illustrates an embodiment in which the solenoid 42 has an upright conical shape.

FIG. 13 illustrates an embodiment in which the solenoid 42 is combined with a planar helical winding 120. The planar helical winding has the effect of reducing the severity with which the solenoid winding 42 concentrates the induction field near the center of the workpiece by distributing some of the RF power somewhat away from the center. This feature may be useful in cases where it is necessary to avoid over-correcting for the usual center null. The extent of such diversion of the induction field away from the center corresponds to the radius of the planar helical winding 120. FIG. 14 illustrates a variation of the embodiment of FIG. 13 in which the solenoid 42 has an inverted conical shape as in FIG. 11. FIG. 15 illustrates another variation of the embodiment of FIG. 13 in which the solenoid 42 has an upright conical shape as in the embodiment of FIG. 12.

The RF potential on the ceiling 52 may be increased, for example to prevent polymer deposition thereon, by reducing its effective capacitive electrode area relative to other electrodes of the chamber (e.g., the workpiece and the sidewalls). FIG. 16 illustrates how this can be accomplished by supporting a smaller-area version of the ceiling 52' on an outer annulus 200, from which the smaller-area ceiling 52' is insulated. The annulus 200 may be formed of the same material (e.g., silicon) as the ceiling 52' and may be of a truncated conical shape (indicated in solid line) or a truncated dome shape (indicated in dashed line). A separate RF power supply 205 may be connected to the annulus 200 to permit more workpiece center versus edge process adjustments.

FIG. 17A illustrates a variation of the embodiment of FIG. 5 in which the ceiling 52 and side wall 50 are separate semiconductor (e.g., silicon) pieces insulated from one another having separately controlled RF bias power levels applied to them from respective RF sources 210, 212 to enhance control over the center etch rate and selectivity relative to the edge. As set forth in greater detail in above-referenced U.S. application Serial No. 08/597,577 filed February 2, 1996 by Kenneth S. Collins et al., the ceiling 52 may be a semiconductor (e.g., silicon) material doped so that it will act as an electrode capacitively coupling the RF bias power applied to it into the chamber and simultaneously as a window through which RF power applied to the solenoid 42 may be inductively coupled into the chamber. The advantage of such a window-electrode is that an RF potential may be established directly over the wafer (e.g., for controlling ion energy) while at the same time inductively coupling RF power directly over the wafer. This latter feature, in combination with the separately controlled inner and outer solenoids 42, 90 and center and peripheral gas feeds 64a, 64b greatly enhances the ability to adjust various plasma process parameters such as ion density, ion energy, etch rate and etch selectivity at the workpiece center relative to the workpiece edge to achieve an optimum uniformity. In this combination, gas flow through individual gas feeds is individually and separately controlled to achieve such optimum uniformity of plasma process parameters.

FIG. 17A illustrates how the lamp heaters 72 may be replaced by electric heating elements 72'. As in the embodiment of FIG. 4, the disposable silicon member is an annular ring 62 surrounding the pedestal 54. Preferably, the annular ring 62 is high purity silicon and may be doped to alter its electrical or optical properties. In order to maintain the silicon ring 62 at a sufficient temperature to ensure its favorable participation in the plasma process (e.g., its contribution of silicon material into the plasma for fluorine scavenging), plural radiant (e.g., tungsten halogen lamp) heaters 77 arranged in a circle under the annular ring 62 heat the silicon ring 62 through a quartz window 78. As described in the above-referenced co-pending application, the heaters 77 are controlled in accordance with the measured temperature of the silicon ring 62 sensed by a temperature sensor 79 which may be a remote sensor such as an optical pyrometer or a fluoro-optical probe. The sensor 79 may extend partially into a very deep hole 62a in the ring 62, the deepness and narrowness of the hole tending at least partially to mask temperature-dependent variations in thermal emissivity of the silicon ring 62, so that it behaves more like a gray-body radiator for more reliable temperature measurement.

FIG. 17B illustrates another variation in which the ceiling 52 itself may be divided into an inner disk 52a and an outer annulus 52b electrically insulated from one another and separately biased by independent RF power sources 214, 216 which may be separate outputs of a single differentially controlled RF power source.

In accordance with an alternative embodiment, a user-accessible central controller 300 shown in FIGS. 17A and 17B, such as a programmable electronic controller including, for example, a conventional microprocessor and memory, is connected to simultaneously control gas flow rates through the central and peripheral gas feeds 64a, 64, RF plasma source power levels applied to the inner and outer antennas 42, 90 and RF bias power levels applied to the ceiling 52 and side wall 50 respectively (in FIG. 17A) and the RF bias power levels applied to the inner and outer ceiling portions 52a, 52b (in FIG. 17B), temperature of the ceiling 52 and the temperature of the silicon ring 62. A ceiling temperature controller 218 governs the power applied by a lamp power source 220 to the heater lamps 72' by comparing the temperature measured by the ceiling temperature sensor 76 with a desired temperature known to the controller 300. A ring temperature controller 222 controls the power applied by a heater power source 224 to the heater lamps 77 facing the silicon ring 62 by comparing the ring temperature measured by the ring sensor 79 with a desired ring temperature

stored known to the controller 222. The master controller 300 governs the desired temperatures of the temperature controllers 218 and 222, the RF power levels of the solenoid power sources 68, 96, the RF power levels of the bias power sources 210, 212 (FIG. 17A) or 214, 216 (FIG. 17B), the wafer bias level applied by the RF power source 70 and the gas flow rates supplied by the various gas supplies (or separate valves) to the gas inlets 64a-d. The key to controlling the wafer bias level is the RF potential difference between the wafer pedestal 54 and the ceiling 52. Thus, either the pedestal RF power source 70 or the ceiling RF power source 212 may be simply a short to RF ground. With such a programmable integrated controller, the user can easily optimize apportionment of RF source power, RF bias power and gas flow rate between the workpiece center and periphery to achieve the greatest center-to-edge process uniformity across the surface of the workpiece (e.g., uniform radial distribution of etch rate and etch selectivity). Also, by adjusting (through the controller 300) the RF power applied to the solenoids 42, 90 relative to the RF power difference between the pedestal 54 and ceiling 52, the user can operate the reactor in a predominantly inductively coupled mode or in a predominantly capacitively coupled mode.

While the various power sources connected in FIG. 17A to the solenoids 42, 90, the ceiling 52, side wall 50 (or the inner and outer ceiling portions 52a, 52b as in FIG. 17B) have been described as operating at RF frequencies, the invention is not restricted to any particular range of frequencies, and frequencies other than RF may be selected by the skilled worker in carrying out the invention.

In a preferred embodiment of the invention, the high thermal conductivity spacer 75, the ceiling 52 and the side wall 50 are integrally formed together from a single piece of crystalline silicon.

Referring again to FIG. 5, a preferred plasma processing chamber includes a window/electrode 52. The window/electrode 52 is fabricated from semiconducting material as described in detail in the above-referenced applications so that it may function as both a window to RF electromagnetic or inductive power coupling from one or more external (outside chamber) antennas or coils to the plasma within the chamber and as an electrode for electrostatically or capacitively coupling RF power to the plasma within the chamber (or for terminating or providing a ground or return path for such capacitive or electrostatic coupling of RF power) or for biasing the workpiece or wafer.

The window/electrode 52 may be any shape as described in the above-referenced applications, but in this example is approximately a flat disc which may optionally include a cylindrical wall or skirt extending outward from the disk, such as for plasma confinement as described in the above-referenced applications.

The window/electrode 52 is interfaced to the heat sink 74 through the heat transfer material 75. Typically the heat sink 74 is a water cooled metal plate, preferably a good thermal conductor such as aluminum or copper, but may optionally be a non-metal. The heat sink 74 typically a cooling apparatus preferably of the type which uses a liquid coolant such as water or ethylene-glycol that is forced through cooling passages of sufficient surface area within the heat sink 74 by a closed-loop heat exchanger or chiller. The liquid flow rate or temperature may be maintained approximately constant. Alternatively, the liquid flow rate or temperature may be an output variable of the temperature control system.

Preferably, radiant heating is used to apply heat to the window/electrode. The radiant heaters 72 are a plurality of tungsten filament lamps utilizing a quartz envelope filled with a mixture of halogen and inert gases. Radiant heaters are preferred to other heater types because thermal lag is minimized: The thermal capacitance of a tungsten filament lamp is very low, such that the time response of filament temperature (and thus of power output) to a change in power setting is short (<1 second), and since the heat transfer mechanism between lamp filament and load is by radiation, the total thermal lag for heating is minimized. In addition, since the heat transfer mechanism between lamp filament and load is by radiation, the total thermal lag for heating is minimized. In addition, since the thermal capacitance of a tungsten filament lamp is very low, the amount of stored thermal energy in the lamp is very low, and when a reduction in heating power is called for by the control system, the filament temperature may be quickly dropped and the lamp output power thus also quickly drops. As shown in FIG. 5, the lamps 72 directly radiate the load (the window/electrode 52) for the fastest possible response. However, alternatively, the lamps 72 may radiate the heat transfer material 75. Lamp heating may be provided in more than one zone, i. e. lamps at two or more radii from the axis of the window/electrode to improve thermal uniformity of window/electrode. For maximum thermal uniformity, lamps in the two or more zones may be provided with separate control, each zone utilizing its own temperature measurement, control system, and output transducer. This is especially useful when the heat flux spatial distribution from inside the chamber varies depending on process parameters, processes, process sequences, or other boundary conditions.

The heat transfer material 75 may be formed integrally with the window/electrode 52 that is formed of the same material into a single piece structure for elimination of a thermal contact resistance that would be present if heat transfer material 75 and window/electrode 52 were two separate parts. Alternatively, the heat transfer material 75 and the window/electrode 52 may be two parts of same or different materials that are bonded together, (preferably with a high electrical resistivity material since the window/electrode 52 is used for inductive or electromagnetic coupling of RF or microwave power using inductive antennas 90, 92 and/or 42, 44), minimizing the thermal contact resistance between the heat transfer material 75 and the window/electrode 52.

Alternatively, the heat transfer material 75 and the window/electrode 52 may be two parts of same or different

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materials that are interfaced together through a contact resistance. In this case, the heat transfer material 75 is preferably made of a highly thermally conductive material of high electrical resistivity. Additionally, a low product of density and specific heat are preferred. SiC, Si, AlN, and Al_2O_3 are examples.

Properties of SiC are indicated below:

Thermal conductivity	130 watt/meter*Kelvin
Electrical resistivity	$>10^5$ ohm*cm
Specific Heat	0.66 joule/gram*Kelvin
Density	3.2 gram/cm^3

Silicon may also be used, if lightly (not heavily) doped (i.e. 10^{14}/cm^3) and has the following properties:

Thermal conductivity	80 watt/meter*Kelvin
Electrical resistivity	20-100 ohm*cm
Specific Heat	0.7 joule/gram*Kelvin
Density	2.3 gram/cm^3

Aluminum nitride or aluminum oxide are other alternatives.

The heat transfer material 75 may be bonded to the heat sink 74 by techniques well known in the art (e.g., using bonding materials such as thermoplastics, epoxies, or other organic or inorganic bonding materials), without the restriction of requiring high electrical resistivity bonding material in the area proximate the heat sink 74. This provides a very low thermal contact resistance between heat transfer material 75 and heat sink 74.

The heat transfer material 75 also serves to separate the inductive antennas 90, 92 and/or 42, 44 from the heat sink 74 which if it is metal, forms a ground plane or reflector to the induction field generated in the vicinity of each inductive antenna 90, 92 and/or 42, 44. If the heat sink 74 is metal and is too close to the inductive antenna 90, 92 and/or 42, 44, then eddy currents are induced in the ground plane, causing power loss. In addition, the RF currents through the antenna 90, 92 and/or 42, 44 become very large to drive a given RF power, increasing I^2R losses in the circuit. The antennas 90, 92 and/or 42, 44 are each four turns comprised of 3/16" diameter water cooled copper tubing insulated with 1/4" outside diameter teflon tubing yielding coils 1" in height. An acceptable distance between the window/electrode 52 and the metal heat sink 74 is about 2", yielding about a 1" distance between the top of the antenna 90, 92 and/or 42, 44 and the heat sink 74.

As described above, thermal contact resistances between the heat transfer material 75 and the window, electrode 52, and between the heat transfer material 75 and the heat sink 74 can be minimized by bonding the materials together. Also described above was an example of forming the window/electrode 52 and the heat transfer material 75 from a single piece of material, eliminating one thermal contact resistance. However, in some cases, one or both thermal contact resistances cannot be avoided. However, the thermal contact resistance(s) can be minimized in accordance with a feature of the plasma reactor, which will now be introduced.

Thermal contact resistance between two parts is comprised of two parallel elements: 1) mechanical point contact between the parts, and 2) conduction through air (or other medium) between the parts. In the absence of air or other medium, the thermal contact resistance between the two parts is very high and typically unacceptable for heating and/ or cooling of the window/electrode 52 due to the high heat loads imposed on it during typical plasma reactor operation. The presence of air yields a lower thermal contact resistance than mechanical point contact alone, but is typically marginal depending on the effective gap between parts, which is a function of the surface roughness and flatness of both parts. For air in the high pressure continuum regime wherein the mean-free-path in the gas is small relative to the effective gap between parts, the thermal conductivity of the air is invariant with gas pressure, and the thermal conductance per unit area is simply the ratio of the thermal conductivity of air to the effective gap. For air at atmospheric pressure and 100 degrees C, the thermal conductivity is about 0.03 watt/meter*Kelvin. Heat transfer across the gap is limited by the low chamber pressure and by the fact that the mechanical contact between the two parts is only point contact.

In order to improve heat transfer, a thermally conductive gas such as (preferably) helium or another one of the inert gases such as argon, xenon and so forth, can be placed in the gap between the between the heat transfer material 75 and the heat sink 74 and/or in the gap between the heat transfer material 75 and the window/electrode 52, in accordance with a first embodiment of the plasma reactor. The thermally conductive gas in the gap is best pressurized above the chamber pressure to as high as atmospheric pressure, although preferably the pressure of the thermal transfer gas in the gap is between the chamber pressure and atmospheric pressure. Helium is a preferred choice for the thermally conductive gas because helium has a thermal conductivity of about 0.18 watt/meter*Kelvin at atmospheric

pressure and 100 degree C. To minimize thermal contact resistance between the heat transfer material 75 and the heat sink 74, helium can be provided to each interface therebetween through a helium distribution manifold within the heat sink 74, as will be described in detail below in this specification. As will also be described below in detail, an O-ring of small cross-section and low durometer can be used to reduce helium leakage and between heat transfer material
5   75 and heat sink 74. Through-holes from the top surface of the heat transfer material or rings 75 can connect a helium passage from an upper interface between the heat sink 74 and the heat transfer material ring 75, to interface between the heat transfer material ring 75 and the window/electrode 52. Each heat transfer ring 75 may be formed of any good thermal conductor which does not tend to absorb an RF field (e.g., a thermal conductor with relatively high electrical resistivity). One suitable material is silicon carbide, although other materials may be employed which may be semi-
10   conductive or dielectric, such as ceramic materials of the type including silicon nitride, aluminum nitride or aluminum oxide. However, silicon carbide is preferred as the material for the heat transfer rings 75. Helium can be supplied to the aforementioned helium distribution manifold located within heat sink 74 at a pressure somewhat above atmospheric to minimize dilution of helium by air which could otherwise increase the thermal contact resistance.

    Other materials may be used in between the heat transfer material 75 and the window/electrode 52, and between
15   the heat transfer material 75 and the heat sink 74 to minimize thermal contact resistances. Examples are thermally conductive, compliant elastomeric pads such as boron nitride or silicon carbide or silicon or aluminum nitride or aluminum oxide, and similar materials. Metal-impregnated elastomeric pads may be used at the interface adjacent the heat sink 74, but not adjacent the window/electrode 52 for the same reasons explained above that in general a conductor may not be placed adjacent the window electrode 52. Soft metals such as 1100 series aluminum, indium, copper or
20   nickel may be used at the interface adjacent the heat sink 74, but not adjacent the window/electrode 52 for the reasons explained above.

    The cooling capability and heating power requirements are best selected or sized depending on 1) temperature control range required of the window/electrode, 2) the minimum and maximum heat internal loads, 3) the material properties and physical dimensions of the window/electrode, the heat transfer materials, the heat sink plate and the
25   interfaces between heat sink plate, heat transfer materials, and window/electrode, and 4) the temperature of the heat sink. Generally, the cooling capability is sized first for the lowest required temperature of operation of the window/ electrode with the highest internal heat load, and the heating power is then sized to overwhelm the cooling for the highest required temperature of operation of the window/electrode with the lowest internal heat load (typically zero internal heat load).

30   FIG. 18 corresponds to an enlarged view of a portion of FIG. 5 and illustrates one implementation of the foregoing concept of a thermally conductive gas interface at both faces (top and bottom) of the thermally conductive spacer 75 which is not integrally formed with the semiconductor window electrode 52. In FIG. 18, the overlying cold plate 74 sandwiches plural cylindrical spacer rings 75 with the underlying semiconductor window electrode 52 as illustrated in FIG. 5. Each spacer or torus 75 can be a material different from the semiconductor window electrode 52, as discussed
35   above. A manifold 1000 is formed in the cold plate 74 into which a thermally conductive gas such as helium may be supplied from a source 1010 under positive pressure. Preferably, but not necessarily, the positive pressure of the source 1010 is selected so as to maintain the pressure within the thin gap between the two parts significantly above the reactor chamber pressure but below atmospheric pressure. Gas orifices 1020 connect the manifold 1000 to the top interface 1030 between the cold plate 74 and the spacer 75, permitting the thermally conductive gas (e.g., Helium) to fill the
40   voids in the interface 1030. An axial passage 1040 is provided through the spacer 75 between its top and bottom faces. The axial passage 1040 connects the top interface 1030 with a bottom interface 1050 between the bottom face of the spacer 75 and the underlying semiconductor window electrode 52. The axial passage 1040 permits the thermally conductive gas to flow from the top interface 1030 to the bottom interface 1050 to fill voids in the bottom interface 1050, so that the thermally conductive gas fills voids in both the top and bottom interfaces 1030, 1050. By the source 1010
45   maintaining the thermally conductive gas manifold 1000 under positive pressure (e.g., 5 psi higher than the chamber pressure), the gas flows to both interfaces 1030, 1050. In order to reduce or prevent leaking of the thermally conductive gas from the interfaces 1030, 1050, small cross-section O-rings 1070, 1080 are sandwiched in the top and bottom interfaces, respectively, at the time of assembly. The O-rings 1070, 1080 define nearly infinitesimally thin gas-containing volumes in the respective interfaces 1030, 1050 in communication with the respective gas manifold 1000, 1040.

50   FIG. 19 illustrates how the embodiment of FIG. 18 is modified to accommodate an array of conductive torus spacers 75 integrally formed with the semiconductor window electrode 52. In this case, the only interface to be filled by the thermally conductive gas is the top interface 1030.

    FIG. 20 corresponds to an enlarged view of a portion of FIG. 5 and illustrates one implementation of the foregoing concept of a thermally conductive solid interface material at both faces (top and bottom) of the thermally conductive
55   spacer 75 which is not integrally formed with the semiconductor window electrode 52. In FIG. 18, the overlying cold plate 74 sandwiches plural cylindrical spacer rings 75 with the underlying semiconductor wi.ndow electrode 52 as illustrated in FIG. 5. Each spacer or torus 75 can be a material different from the semiconductor window electrode 52, as discussed above. A thermally conductive solid interface material layer 1085, 1090 is placed in either or both the top

and bottom interfaces 1030, 1050, respectively. If a solid material layer is placed in only one of the top and bottom interfaces 1030, 1050, then the remaining interface may be filled with a thermally conductive gas in the manner of FIG. 18. However, FIG. 20 illustrates the case in which a thermally conductive solid interface material layer is in both interfaces 1030, 1050. As discussed above, the solid interface material layer 1085 in the top interface 1030 may be a soft
5   metal, but the solid interface material layer 1090 in the bottom interface 1050 cannot be highly electrically conductive because it is next to the electrode 52. The top layer 1085 may be soft aluminum, indium, copper or nickel or an elastomer impregnated with powders or particles of such metals. Either one of the top and bottom layers 1085, 1090 may be an elastomer impregnated with powder or particles of a thermally conductive electrically insulating material such as boron nitride, high electrical resistivity (e.g., bulk) silicon carbide or silicon, aluminum nitride, aluminum oxide and like mate-
10 rials. Alternatively, either one or both of the material layers 1085, 1090 may be a bonding material, such as thermoplastic, epoxy or an organic or inorganic bonding material.

FIG. 21 illustrates how the embodiment of FIG. 20 is modified to accommodate an array of conductive torus spacers 75 integrally formed with the semiconductor window electrode 52. In this case, the only interface to be filled is the top interface 1030.

15 The invention also solves a severe cooling problem with heated parts inside the reactor chamber which are difficult to cool, such as the heated disposable ring 62 of polymer-hardening precursor material described above with reference to FIG. 5. (The ring 62 may be heated only by plasma heating if no heater is provided, and still require cooling.) It also solves a problem of heating parts inside the reactor chamber which are difficult to heat directly.

Referring to FIGS. 22 and 23, a cold plate 1100 directly beneath the ring 62 and in thermal contact has internal
20 coolant jackets 1110 which receive coolant from a coolant circulation pump 1120. The interface 1130 between the cold plate 1110 and the ring 62 is filled with a thermal conductivity enhancing substance such as a thermally conductive gas (as in FIG. 22) or a thermally conductive solid material layer 1140 (as in FIG. 23). The thermally conductive gas may be any gas capable of conducting heat, such as an inert gas or even a gas similar to the process gas employed in the reactor chamber, although an inert gas such as helium is preferred. In the case of the embodiment of FIG. 22
25 employing the thermally conductive gas, a manifold 1150 through the cold plate 1100 is connected to a thermally conductive gas source 1160 which supplies thermally conductive gas through the manifold 1160 into the interface 1130. Leakage of the gas from the interface 1130 is preferably controlled to reduce or prevent loss by sandwiching an elastomeric low-cross-section O-ring 1070' between the cold plate 1100 and silicon ring 62 at the time the ring is put into its place.

30 While helium is preferred as the thermally conductive gas in the gap, in the case of application to heated or cooled parts inside the sub-atmospheric reactor chamber, any gas, including a processing gas, could suffice at a pressure greater than the chamber pressure but below atmospheric. In such a case, the gas may be allowed to leak into the chamber so that the use of a peripheral seal such as an O-ring or elastomer may not be necessary. Since the thermally conductive gas (or "thermal transfer gas") is pressurized above the chamber pressure, some clamping force must be
35 applied. Such a clamping force can be mechanical or may be electrostatically induced between the plate 1100 and the ring 62. Such an electrostatic clamping feature would require a material which is at least partially electrically insulating to be placed between the plate 1100 and the ring 62. Such a feature can eliminate the need for a peripheral seal to control leakage of the thermally conductive gas. Such an electrostatic clamping feature is described below in this specification with reference to FIG. 26.

40 The thermally conductive gas can be derived from any suitable source. For example, if the wafer pedestal employs helium cooling underneath the wafer, then a common helium source may be employed for cooling the wafer as well as other items (such as the ring 62) inside the chamber.

In the embodiment of FIG. 23, the layer of solid thermally conductive material 1140 may be soft aluminum, indium, copper or nickel or an elastomer impregnated with powders or particles of such metals or it may be an elastomer
45 impregnated with powder or particles of a thermally conductive electrically insulating material such as boron nitride, high resistivity (e.g., bulk) silicon carbide or silicon, aluminum nitride, aluminum oxide and like materials.

The plasma reactor also concerns cooling chamber walls and chamber liners in a similar manner. Referring to FIG. 24, the chamber side wall 50 in any of the reactors discussed above may be cooled by an exterior cold plate 1210 adjacent a portion of the exterior of the wall 50. The cold plate includes internal coolant jackets 1220 through which
50 coolant is recirculated by a coolant pump 1230. The interface 1240 between the cold plate 1210 and the side wall 50 is filled with a thermally conductive gas (such as helium) fed through a manifold 1245 through the cold plate 1210 into the interface 1240 from a gas source 1250 which maintains the gas at a positive pressure. Leakage of the thermally conductive gas from the interface 1240 is reduced or prevented by an O-ring 1260 sandwiched between the cold plate 1210 and the side wall 50 at the time of assembly. The O-ring 1260 defines a gas-containing volume of the interface
55 1240 which is nearly infinitesimally thin and in communication with the manifold 1245.

An interior chamber liner 1300 may be cooled by heat conduction to a cooled body, such as the side wall 50. In accordance with the plasma reactor, such cooling is enhanced by filling the interface 1310 between the liner 1300 and the interior surface of the side wall 50 with a thermally conductive gas such as helium. For this purpose, a radial narrow

gas channel 1320 is provided through the side wall 50 to provide gas flow between the interface 1240 on the external side wall surface and the interface 1310 on the internal side wall surface. The thermally conductive gas supplied through the manifold 1245 fills the external surface interface 1240 and, through the channel 1320, fills the internal surface interface 1310 between the liner 1300 and the side wall 50. To prevent or reduce gas leakage, an O-ring 1370 is
5   sandwiched between the side wall 50 and the liner 1300 at the time of assembly. The O-ring 1370 defines a nearly infinitesimally thin gas-containing volume within the interface 1310 in communication with the gas channel 1245 in the side wall 50.

FIG. 25 illustrates how the embodiment of FIG. 24 is modified by substituting a solid material layer 1370, 1380 in each of the interfaces 1240 and 1310, respectively, instead of the thermally conductive gas. In the embodiment of FIG.
10   25, each layer 1370, 1380 of solid thermally conductive material may be soft aluminum, indium, copper or nickel or an elastomer impregnated with powders or particles of such metals or it may be an elastomer impregnated with powder or particles of a thermally conductive electrically insulating material such as boron nitride, high resistivity (e.g., bulk) silicon carbide or silicon, aluminum nitride, aluminum oxide and like materials.

FIG. 26 illustrates how the embodiment of FIG. 22 may be modified to include the feature of electrostatic clamping
15   of the ring 62 to the cold plate 1100. In FIG. 26, a dielectric layer 1410 is inserted between the polymer-hardening precursor ring 62 and the cold plate 1100, and an electrostatic clamping voltage is applied to the cold plate 1100 from a D.C. voltage source 1420 through a clamping switch 1430. Introduction of the insulating or dielectric layer 1410 creates a gap 1130a between the cold plate 1100 and the insulating layer 1410 and a gap 1130b between the ring 62 and the insulating layer 1410. The insulating layer 1410 has passageways 1412 therethrough so that gas supplied
20   from the passageway 1150 into the gap 1130a can flow into the other gap 1130b. While FIG. 26 shows O-rings 1070' sealing both gaps 1130a and 1130b, such O-rings may not be necessary, depending upon the electrostatic clamping force induced.

The plasma reactor provides a great improvement (by a factor of about 6 in the case of the introduction of helium) in thermal conductivity across the interface between heat-receiving elements of the reactor either inside the chamber
25   (such as chamber liners, disposable silicon rings) and outside the chamber (such as window electrodes, side walls) and a cooling plate or cold sink. As a result, the automated control of temperature of many critical parts of the plasma reactor is improved to a new capability exceeding that of the prior art. The invention accomplishes this in one or a combination of two characteristic modes at the various interfaces: (a) the introduction of a thermally conductive gas into the interface and (b) the introduction of a thermally conductive solid layer in the interface. This, in combination
30   with efficiently controlled heating of the same elements, permits accurate feedback control of the temperature of each such element thus heated and cooled.

In selecting the heat transfer materials and/or physical dimensions of the reactor, the cooling conductance required (G) is determined as follows:

35

$$G = \text{total } \underline{\text{maximum}} \text{ internal heat load (watts) / Delta-T1 (degree C)}$$

where

40

$$\text{Delta-T1} = \text{Difference between heat sink temperature}$$

$$\text{and } \underline{\text{minimum}} \text{ window/electrode temperature.}$$

45   Alternatively, if the heat transfer materials and physical dimensions have already been chosen, then the required heat sink temperature may be trivially calculated by rearranging the above equation for Delta-T1 as function of G.
Heating power is then determined as follows:

50

$$P = \text{total external heating power required (watts) delivered to control surface,}$$

$$P = (G*\text{Delta-T2}) - \text{Pmin}$$

55   where:

G is the cooling conductance from above (in watts/degree C),
Delta-T2 = Difference between heat sink temperature and $\underline{\text{maximum}}$ window/electrode temperature

16

Pmin is the minimum internal heat load on the window/electrode.

Example 1:

5   The window/electrode 52 and the heat transfer rings 75 are integrally formed as a monolithic piece, and the window/electrode 52 is a flat circular disk 12.81 inches in diameter and 0.85 in thick. Formed integrally with the window/electrode 52 is an array of four concentric cylindrical heat transfer rings (75) 2" high of the following inside and outside diameters:

       1. outer heat transfer ring - 12.80" outside dia., 10.79" inside dia.,
10   2. middle heat transfer ring - 9.010" outside dia., 7.595" inside dia.,
       3. inner heat transfer ring - 5.715" outside dia., 3.940" inside dia.,
       4. center heat transfer ring - 2.260" outside dia., 0.940" inside dia.

       The window/electrode 52 and integral array of concentric cylindrical heat transfer rings 75 are fabricated together
15   from a single ingot of polycrystalline silicon with the following thermal and electrical properties:

Doping level	10^{14}/cm^3, boron or phosphorous
Thermal conductivity	80 watt/meter*Kelvin
Electrical resistivity	from 20 to 100 ohm*cm
Specific Heat	0.7 joule/gram*Kelvin
Density	2.3 gram/cm^3

       A plurality of 750 watt @ 120 volt rms tungsten filament lamps 76 are employed. The number of lamps is selected
25   based on measured 73% efficiency (output power/ac input power) and on 400 watt @ 80 volt rms maximum operating level (for long lamp life). Two heat zones are employed, those on the outer circle comprise one zone (outer), and those on the inner circle and at the center comprise the second (inner) zone. Each zone has its own temperature measurement (a type-K thermocouple spring loaded against the window/electrode surface) and its own output transducer (a phase-angle controller). The lamps, manufactured by Sylvania, are deployed as follows:

30
       15 lamps on a 13.55" diameter circle, equal angular spacing (24 degrees);
       15 lamps on a 6.655" diameter circle, equal angular spacing (24 degrees);
       1 lamp on central axis.

35   The outer lamp circle is surrounded on the outside by a cylindrical polished aluminum reflector that is integral with the heat sink 74.
       The outer solenoid antenna 90 is 4 turns comprised of 3/16" diameter water cooled copper tubing insulated with 1/4" outside diameter teflon tubing yielding coil 1" in height and 10" mean diameter, wound as described in the above-referenced parent application.
40   The inner solenoid antenna 42 is 4 turns comprised of 3/16" diameter water cooled copper tubing insulated with 1/4" outside diameter teflon tubing yielding coil 1" in height and 3.25 mean diameter, wound as described in the above-referenced parent application.
       The heat sink plate 74 is a water cooled aluminum plate maintained at 75 degree C by a closed loop heat exchanger using a 50/50% water/ethylene-glycol mixture at a flow rate of 2 gallons per minute. The heat sink 74 houses lamp
45   sockets and provides cooling for the clamps 76 required due to inherent lamp losses to socket (approximately 27%). The heat sink plate 74 includes feed-through for the inner and outer solenoidal antennas 42, 90. The heat sink 74 also functions as a ground plane for the antennas 42, 90. The heat sink plate 74 includes O-ring grooves to accommodate 0.139 inch diameter, 30 durometer soft O-rings deployed just inside the outer diameter of each heat transfer ring 75 and just outside the inner diameter of each heat transfer ring 75. The heat sink 74 is mounted on top of the integral
50   array of concentric cylindrical heat transfer rings 75. Surface roughness of both surfaces (the bottom of the heat sink 74 and the top of heat transfer rings 75) is less than a micro-inch. Flatness of each surfaces is less than 0.0005 inch. The effective gap between the bottom of the heat sink and the top of the heat transfer rings is less than 0.001 inch.

Example 2:

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       The window/electrode 52 and the heat transfer rings 75 are separate pieces formed of different materials. The window/electrode 52 is a flat circular disk 14.52 inches in diameter and 0.85 inches thick. A separate array of 4 concentric cylindrical heat transfer rings 75 2" high of the following inside and outside diameters is placed in between the

heat sink plate and the window electrode:

1. outer heat transfer ring - 12.70" outside dia., 10.67" inside dia.,
2. middle heat transfer ring - 8.883" outside dia., 7.676" inside dia.,
3. inner heat transfer ring - 5.576" outside dia., 3.920" inside dia.,
4. center heat transfer ring - 2.080" outside dia., 1.050" inside dia.

The window/electrode 52 is fabricated from a single ingot of polycrystalline silicon with the following thermal and electrical properties:

Doping level	10^{14}/cm^3, boron or phosphorous
Thermal conductivity	80 watt/meter*Kelvin
Electrical resistivity	20-100 ohm*cm
Specific Heat	0.7 joule/gram*Kelvin
Density	2.3 gram/cm^3

The array of concentric cylindrical heat transfer rings 75 are fabricated from SiC (silicon carbide) with the following thermal and electrical properties:

Thermal conductivity	130 watt/meter*Kelvin
Electrical resistivity	105 ohm*cm
Specific Heat	0.655 joule/gram*Kelvin
Density	3.2 gram/cm^3

A plurality of 750 watt @ 120 volt rms tungsten filament lamps are employed. The number of lamps is selected based on measured 73% efficiency (output power/ac input power) and 400 watt @ 80 volt rms maximum operating level (for long lamp life). Two heat zones are employed, those on the outer circle comprise one zone (outer), and those on the inner circle and at the center comprise the second (inner) zone. Each zone has its own temperature measurement (a type-K thermocouple spring loaded against the window/electrode surface) and its own output transducer (a phase-angle controller). The lamps 76, manufactured by Sylvania, are deployed as follows:

15 lamps on 13.55" diameter circle, equal angular spacing (24 degree);
15 lamps on 6.626" diameter circle, equal angular spacing (24 degree);
1 lamp on central axis.

The outer lamp circle is surrounded on the outside by a cylindrical polished aluminum reflector that is integral with the heat sink.

The outer solenoid antenna 90 is four turns comprised of 3/16" diameter water cooled copper tubing insulated with 1/4" outside diameter teflon tubing yielding coil 1" in height and 10" mean diameter, wound as described in the above-referenced parent application.

The inner solenoid antenna 42 is four turns comprised of 3/16" diameter water cooled copper tubing insulated with 1/4" outside diameter teflon tubing yielding coil 1" in height and 3.25 mean diameter, wound as described in the above-reference parent application.

The heat sink plate 74 is a water cooled aluminum plate maintained at 75 degrees C by a closed loop heat ex-changer using a 50/50% water/ethylene-glycol mixture at a flow rate of 2 gallons per minute. Heat sink houses lamp sockets and provides cooling for the lamps, required due to inherent lamp losses to socket (approximately 27%). The heat sink plate 74 includes feed-through for the aforementioned inner and outer solenoidal antennas 42, 90. The heat sink 74 also functions as a ground plane for the antennas. The heat sink plate 74 and the window/electrode 52 include O-ring grooves to accommodate 0.139 inch diameter, 30 durometer soft O-rings deployed just inside the outer diameter of each heat transfer ring 75 and just outside the inner diameter of each heat transfer ring 75. The heat sink 74 is mounted on top of the array of concentric cylindrical heat transfer rings 75. Surface roughness of all surfaces (bottom of the heat sink and top of the heat transfer rings, bottom of the heat transfer rings and top of the window/electrode) is less than a micro-inch. Flatness of each surface is less than 0.0005 inch. The effective gap between the bottom of the heat sink and the top of the heat transfer rings is less than 0.001 inch. The effective gap between the bottom of the heat transfer rings and the top of the window/electrode is less than 0.001 inch.

DETAILED DESCRIPTION RELATING TO THE PRESENT INVENTION: Removable Plasma Confinement Magnet Modules:

Referring now to FIG. 27, the plasma confinement magnets 80, 82 protecting the pumping annulus 60 may each be encased in a modular (removable) magnet liner module. Thus, a magnet liner module 2010 holds the plasma confinement magnet 80 while a magnet liner module 2020 holds the plasma confinement magnet 82. Each magnet liner module 2010, 2020 is preferably formed of a non-magnetic metal such as aluminum. The silicon ceiling 52 rests on the liner module 2010 and the liner module 2010 rests on the chamber side wall or body 50. An RF gasket 2012 and an O-ring 2014 are pressed between the liner module 2010 and the ceiling 52. Another RF gasket 2016 and another O-ring 2018 are pressed between the liner module 2010 and the chamber body 50. Referring to FIG. 28, each liner module 2010, 2020 has an opening or rectangular-shaped depression 2030 in which the magnet (e.g., the magnet 80) resides. The magnet 80 is bonded to the outward-facing surface of the opening 2030 by a bonding layer 2040 (which may be an epoxy material, for example) between the magnet 80 and the magnet liner module. The magnet 80 is protectively sealed inside the opening 2030 by an aluminum cover 2050 which can be laser welded or E-beam welded to the magnet liner module so as to seal the opening. This forms a welding layer 2060 between the cover 2050 and the liner module. The liner modules 2010, 2020 are placed on the interior walls of the pumping annulus 60 so that the magnets 80, 82 are as close as possible to their regions of interaction with the plasma. One advantage of this embodiment is that the magnets 80, 82, although at a minimum distance from their plasma interaction regions, are protected from the plasma by being sealed inside their respective liner modules 2010, 2020. Another advantage is that the magnets are thermally coupled to cooled bodies (i.e., the chamber walls) by contact of the thermally conductive (aluminum) liner modules with the walls, so that the magnets 80, 82 are cooled. This enables the plasma confinement magnets to be maintained well below their Curie temperature and therefore remain effective. For this purpose, in addition to the coolant passages 74a through the cooling plate 74, additional coolant passages 2070 can be provided in the chamber walls near the areas of contact with the plasma confinement magnet liner modules 2010, 2020. To further enhance heat transfer from the magnet liner module to the chamber wall, each liner module 2010, 2020 may be fastened to the adjoining chamber wall by a fastener 2080. One feature of the magnet liner modules 2010, 2020 is their easy removability from the chamber assembly for easy cleaning.

In addition to protecting the pump annulus 60 by the plasma confinement magnet pair 80, 82, the reactor may have a wafer slit valve 2082 which can be protected by another pair of plasma confinement magnets 2084, 2086 encased in a similar pair of plasma confinement magnet liner modules 2088, 2090 each employing the features discussed above with reference to FIG. 28.

The plasma confinement magnet pairs can be employed to prevent plasma leakage through any gap in the physical barrier (chamber wall) such as the wafer slit valve, the gas inlet to the chamber, the pumping annulus, windows of the chamber or even the chamber wall itself. One example of how plasma leakage through gas inlets of the chamber can be prevented by plasma confinement magnets is illustrated in FIG. 27 for an overhead center gas feed 2092. The center gas feed 2092 accommodates a liner module 2094 holding at least a pair of plasma confinement magnets 2096a, 2096b facing one another across the center gas feed 2092. Alternatively, the liner module 2094 can be divided into two separable modules, each holding one of the pair of plasma confinement magnets 2096a, 2096b. The center gas feed liner module 2094 can be aluminum, although one option could be to employ silicon in the liner module 2094 for compatibility with the silicon ceiling 52. Each orifice or gas inlet of the reactor can have a similar plasma confinement magnet liner module.

Instead of placing the center gas feed plasma confinement magnet inside a liner module within the ceiling, the magnets could be placed on top of the ceiling without using any liner module.

The liner modules referred to herein may not necessarily by liners of the chamber (e.g., removable pieces covering the chamber interior surfaces) but may instead simply serve as protective housings for the plasma confinement magnets without serving as liners.

The magnetic orientations of the plasma confinement magnet pairs referred to above may be in accordance with any of the options illustrated in FIGS. 31A-31E, corresponding to the disclosure of one of the above-referenced co-pending applications, namely U.S. Serial No. 08/597,577.

Overcoming Non-Uniform Heating/Cooling of Ceiling:

Referring again to FIG. 27, the heat transfer from the ceiling 52 to the cold plate 74 through each thermally conductive ring 75 depends upon the thermal resistance across the gap 74' between the cooling plate 74 and the thermally conductive ring 75. This resistance predominantly depends upon the gap 74' which in turn depends upon surface flatness and the force with which the ring 75 is held against the cooling plate 74. Unless the thermal resistances across all of the gaps 74' between the thermally conductive rings 75 and the cooling plate 74 are at least nearly equal, heat transfer to the cooling plate 74 from different ones of the concentric thermally conductive rings 75 will be different.

Because different areas of each of the rings 75 contact different areas of the ceiling 52, the disparity in heat transfer by the different rings 75 produces a spatially non-uniform distribution of heat transfer across the surface of the ceiling 52. Thus, assuming uniform heating of the ceiling 52 by the distributed heater lamps 72, the non-uniform distribution of heat transfer across the ceiling 52 will produce temperature differences across the ceiling 52, a significant problem.

5   It seems nearly impossible to avoid such a problem: a fairly uniform temperature distribution across the 15 inch diameter ceiling 52 would require the gap between the cooling plate 74 and the rings 75 to be maintained within a tolerance of one to two tenths of a mil (1/1000 inch) across the entire diameter of the cooling plate (where the gap is filled with air). In reality, with silicon-carbide materials, the tolerance is no better than two to three tenths and with aluminum materials the tolerance is no better than 5 tenths or more. Therefore, depending upon how tightly the cooling plate 74 and the

10   thermally conductive rings 75 are fastened together, the ceiling 52 can experience an excessive temperature difference across its diameter.

What is needed is an interface between the cooling plate 74 and each thermally conductive ring 75 which permits the cold plate 74 to be hinged upwardly from the thermally conductive rings 75 (without having to break any electrical or gas or coolant connections or couplings) and which provides uniform thermal contact resistance. Such rapid remov-

15   ability is necessary for periodic maintenance or replacement of the ceiling. Therefore, attempting to provide an interface having uniform thermal contact resistance by bonding the thermally conductive rings 75 to the cold plate 74 is not a viable solution, as this would prevent removability. Uniformity of thermal contact resistance could be enhanced by employing a soft aluminum material in the gap 74', but this would require too great a compressive force between the cold plate 74 and the thermally conductive rings 75 (because of the large variation in the width of the gap 74' across

20   the cold plate 74). Uniformity of contact resistance could be enhanced by employing a thermally conductive grease in the gaps 74', but this would be too messy and risk high contaminant levels in the plasma process.

We have found that employing a thermally conductive elastically deforming material such as Grafoil as a thermally conductive layer 3010 within the gap 74' compensates for the poor gap tolerances referred to above in that it provides relatively uniform thermal contact resistance across the diameter of the ceiling 52 without requiring excessive com-

25   pressive force between the cold plate 74 and the thermally conductive rings 75. (Grafoil is a product sold by UCAR Carbon Co., Inc., P.O. Box 94364, Cleveland, Ohio 44101). The required compressive force is reduced by reducing the thickness of the elastically deformed thermally conductive layer 3010 placed inside the gap 74'. (The layer 3010 is elastically deformed by the compression between the cold plate 74 and the thermally conductive rings 75. However, the thickness of the layer 3010 cannot be reduced beyond a minimum thickness necessary to enable the elastically

30   deformable thermally conductive material of the layer 3010 to compensate for a large tolerance in gap thickness. Thus, there is a tradeoff between thickness and stiffness. To optimize this tradeoff, we have found a preferred thickness of the elastically deformed thermally conductive layer 3010 to be within a range of about 0.04 to 0.16 inch and more preferably within a range of about 0.06 to 0.125 inch.

One problem we have encountered with the elastically deformed thermally conductive layer 3010 is that it absorbs

35   RF power from the inductive coils 42, 90 and shunts the heat to the cooling plate 74. We have solved this problem by placing an electrically conductive layer 3020 between the thermally conductive layer 3010 and the thermally conductive ring 75 which reflects the RF inductive field from the coils 42, 90, and thereby prevents absorption of RF power by the thermally conductive layer 3010. We prefer the electrically conductive layer 3020 be aluminum and have a thickness on the order of approximately 1-10 mils and preferably between about 2-3 mils. Conveniently, the supplier of Grafoil

40   referred to above supplies Grafoil tape with an aluminum coating on one side of the Grafoil tape. A suitable material other than aluminum can be used as the reflective layer 3020, such as copper, nickel, silver or gold for example. Such a material should meet the dual requirement of sufficient heat conductivity and high reflectance to the inductive RF field from the coils 42, 90.

The advantages of the preferred material, aluminum-layered Grafoil tape, for the thermally conductive layer 3010,

45   is that it meets the requirement for a thermally conductive material which is elastically deformable, thin and readily separable from both the cooling plate 74 and the thermally conductive ring 75, while its aluminum coating provides a good reflector to the RF inductive field.

In accordance with one possible alternative, in addition to placing an elastically deformed thermally conductive layer 3010 between the cooling plate 74 and the thermally conductive rings 75, thermal contact resistance across the

50   gap 75' between each thermally conductive ring 75 and the semiconductor ceiling 52 could be improved employing a similar layer of elastically deformable thermally conductive material in the gap 75' between the ceiling 52 and each thermally conductive ring 75. Thus, an elastically deformed thermally conductive layer 3035 (such as Grafoil) can be placed in the gap 75' between each thermally conductive ring 75 and the ceiling 52. However, the semiconductor ceiling 52 and the thermally conductive rings 75 preferably constitute a single modular assembly so that the rings 75 preferably

55   are not separable from the ceiling 52, because the rings 75 and the ceiling 52 are bonded together to optimize heat transfer.

20

Modularity and Enhanced Productivity

Modularity (separability) is important for ease of maintenance. An upper assembly 3040 including the cooling plate 74, the source power coils 42, 90 and the heater lamps 72 is separately hingeable from a lower assembly 3050 including the thermally conductive rings 75 and the semiconductor ceiling 52. The lower assembly 3050 itself is hingeable from the chamber. The separability of the upper assembly 3040 and the lower assembly 3050 permits the semiconductor ceiling 52 to be replaced without breaking fluid and electrical connections. Such replacement is necessary after processing on the order of 100,000 wafers. The separability of the lower assembly 3050 (leaving the upper assembly attached to it) permits access to the plasma confinement magnet modules 2010, 2020 for removal and cleaning as well as to the chamber interior surfaces for wiping, without having to break fluid or electrical connections. This may be required after processing on the order of 3,000 to 4,000 wafers.

Not shown in the drawing of FIG. 27 are the hinging apparatus (for hinging the cooling plate 74 and for hinging the ceiling 52) and the clamping apparatus for clamping the cooling plate 74 onto the thermally conductive rings 75 and for clamping the silicon ceiling 52 onto the magnet liner module 2010.

Electrostatic Chuck with Semiconductor Lift Pins:

In accordance with another aspect of the invention, an electrostatic chuck is enhanced with a feature which eliminates the necessity of discharging the wafer through the plasma when de-chucking the wafer. Conventionally, to de-chuck a wafer from an electrostatic chuck, the following steps must be performed:

(1) release the He gas vacuum between the wafer and the electrostatic chuck;
(2) ground the back side of the electrostatic chuck;
(3) wait until the wafer discharges through the plasma, and then remove the wafer.

The problem with this method is that a wafer having a thick dielectric coating slows down the discharge of the wafer through the plasma, or prevents a thorough discharge, so that excessive force is required to remove the wafer. Or, if too much charge has accumulated on the wafer, the wafer cannot be thoroughly discharged within a practical amount of time.

The present invention overcomes the foregoing problems with conventional electrostatic chucks by providing grounded semiconductor pins or lift pins within the chuck that are raised to contact the backside of the wafer whenever it is desired to remove or de-chuck the wafer. The wafer is discharged by ohmic contact or tunneling or surface leakage from the backside of the wafer to the semiconductor pins. Referring to FIG. 27, the electrostatic chuck 54 holds the wafer 56 down by electrostatic force through an electric field applied across an electrostatic chuck dielectric layer 54a between the wafer 56 and the chuck 54. The electrostatic force may be produced by charging the electrostatic chuck 54 by temporarily connecting it to a voltage source, as indicated in the drawing. The electrostatic chuck 54 is enhanced with the addition of one or more plural semiconductor lift pins 4010 extending upwardly through the chuck 54 toward the backside of the wafer. A lift spider 4020 supporting the opposite ends of the semiconductor pins 4010 is moved by an actuator 4030 up or down so as to move the semiconductor lift pins 4010 up or down as desired. In order to de-chuck the wafer, the semiconductor lift pins are grounded and the actuator 4030 moves the lift spider 4020 upwardly until the semiconductor lift pins contact the backside of the wafer. The wafer then discharges very rapidly, after which the wafer can be removed. The advantage is that there is little or no risk of wafer breakage during de-chucking because the wafer is thoroughly discharged regardless of whether the wafer has a thick dielectric coating or has a large accumulated charge. Preferably, the semiconductor lift pins 4010 are silicon carbide, although they may be any suitable semiconductor material such as silicon, for example. The silicon carbide material may be formed by chemical vapor deposition. A single such pin may suffice in many cases.

The advantage of semiconductor grounding or lift pins over metal pins is that the conductivity of a metal is so great that a resistor must be employed to avoid arcing at the wafer backside surface, and even with such a resistor a metal pin provides points along its length for arcing or gas breakdown and for shunting currents resulting therefrom to other places in the reactor. Moreover, metal pins are more subject to wear. In contrast, semiconductor (e.g., silicon carbide) lift pins have a higher electrical resistivity and therefore do not pose as great a risk for arcing and are more durable.

Electrostatic Chuck Silicon Carbide Collar

The electrostatic chuck 54 may be further enhanced with the addition of a silicon carbide collar 4050 around its periphery. The silicon carbide collar 4050 may be formed by chemical vapor deposition. The silicon carbide collar 4050 is between the electrostatic chuck 54 and the heated silicon ring 62. The collar 4050 preferably is co-extensive in height with the electrostatic chuck 54 as shown in the drawing. However, the collar 4050 may, in some embodiments, extend

above the plane of the chuck 54 so as to cover the edge of the wafer supported on the chuck 54.

The semiconductor collar 4050 prevents etching of the electrostatic chuck which otherwise could lead to contamination and force expensive frequent replacement of the electrostatic chuck. Moreover, the semiconductor materials of the collar 4050 is less susceptible to etching (or etches more slowly) than other materials, such as quartz for example.

Slit in Heated silicon Ring

The heated silicon ring 62 may be enhanced by the provision of a radial slit 4060 therethrough, best shown in FIG. 29. The slit 4060 permits greater thermal expansion of the silicon ring 62 without breakage.

RF Induction Coil with Azimuthally Uniform Number of Windings

As previously disclosed in the co-pending application, an inductive antenna may be formed of multiple co-planar circular windings (as distinguished from a single helical winding). Each winding is connected to its neighbor by a step in the conductor between adjacent planes. This is illustrated in FIG. 30, in which stacked multiple planar circular windings 5010 start with one end 5020 descending from an adjacent plane and terminate with the other end 5040 descending into the next adjoining plane. The ascending and descending ends 5020, 5040 define a step 5060 in the monolithic conductor 5065 from which the multiple windings 5010 are formed. The number of windings in the stack is inherently non-uniform because of the step 5060 in the conductor 5065. This is due, in part, to the abrupt departure of the top winding 5010a from the stack by its sharp turn from a direction parallel to the planes of the windings 5010 to a perpendicular direction. Such an abrupt departure creates a deficiency in the number of windings stacked bottom to top, giving rise to the non-uniformity.

In accordance with the present invention, this non-uniformity is compensated by running the bottom return leg 5070 of the conductor 5065 along an upwardly ascending arcuate path (e.g., a circular path) extending from one end 5060a to the other end 5060b of the step 5060 in the conductor 5065. The radius of the circular path of the bottom return leg 5070 is such that it contributes a maximum inductance near the step end 5060a where it is most nearly parallel to the planes of the windings 5010 and contributes a minimum inductance near the other step end 5060b where it is most nearly perpendicular to the planes of the windings 5010. The smooth transition in the inductance contribution of the bottom return leg 5070 corresponds to the transition along the length of the step 5060 in the conductor 5065 from one end 5060a having the least number of stacked windings (absent the return leg 5070) to the other end 5060b having the greatest number of stacked windings. This provides optimum uniformity in the effective number of windings.

While the invention has been described in detail by specific reference to preferred embodiments, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.

Claims

1. A plasma reactor comprising:

    a chamber for containing a plasma;
    a passageway communicating with said chamber;
    a first removable plasma confinement magnet module placed adjacent said passageway, said first module comprising:

        a first module housing, and
        a first plasma confinement magnet inside said housing.

2. The reactor of Claim 1 further comprising a second removable plasma confinement magnet module placed adjacent said passageway, said second module comprising:

        a second module housing, and
        a second plasma confinement magnet.

3. The reactor of Claim 2 wherein said first and second modules are located on opposite sides of said passageway.

4. The reactor of Claim 3 wherein said first and second plasma confinement magnets have magnetic orientations which tend to oppose plasma transport or leakage through said passageway.

5. The reactor of Claim 1 wherein said first module housing comprises a relatively non-magnetic thermal conductor.

6. The reactor of Claim 5 wherein said first module comprises aluminum.

7. The reactor of Claim 5 wherein said chamber comprises a chamber body, and wherein said first module housing is in thermal contact with said chamber body.

8. The reactor of Claim 7 further comprising cooling apparatus thermally coupled to said chamber body, whereby to maintain said first plasma confinement magnet below its Curie temperature.

9. The reactor of Claim 1 wherein said reactor further comprises a pumping annulus adjacent of a periphery of said chamber, and wherein said passageway comprises a passageway communicating between said chamber and said pumping annulus.

10. The reactor of Claim 1 wherein said passageway comprises a wafer slit valve.

11. The reactor of Claim 1 wherein said passageway comprises a gas feed inlet.

12. The reactor of Claim 11 wherein said gas feed inlet comprises a center gas feed through a ceiling of said chamber.

13. The reactor of Claim 1 wherein said reactor further comprises a chamber side wall and a chamber ceiling, and wherein said first module housing rests upon said side wall and said ceiling rests upon said first module housing.

14. The reactor of Claim 5 wherein said module housing comprises an opening, said first magnet located inside said opening, said module housing further comprising:

   a bonding layer attaching said first magnet to an interior surface inside said opening, and
   a cover plate covering said opening so as to seal said first magnet inside said first module housing.

15. The reactor of Claim 14 further comprising a welding bond between said cover plate and said first module housing.

16. The reactor of Claim 15 wherein said welding bond is produced by one of: (a) E-beam welding, (b) laser welding.

17. A plasma reactor comprising:

   a reactor chamber enclosure including a ceiling;
   plural cooling rings resting on top of said ceiling;
   a cold plate overlying said plural cooling rings; and
   an elastically deformable thermally conductive layer between each one of said plural cooling rings and said cold plate.

18. The reactor of Claim 17 wherein said elastically thermally conductive layer comprises Grafoil.

19. The reactor of Claim 17 further comprising an RF reflector coating between said elastically deformable thermally conductive layer and each cooling ring.

20. The reactor of Claim 19 wherein said RF reflector coating is thermally conductive.

21. The reactor of Claim 20 wherein said RF reflector coating is electrically conductive.

22. The reactor of Claim 21 wherein said RF reflector coating comprises aluminum.

23. The reactor of Claim 19 further comprising an RF power applicator between said cold plate and said ceiling capable of coupling RF power into said chamber through said ceiling, whereby said reflector coating reflects RF power to prevent its absorption by said elastically deformable layer.

24. An plasma reactor comprising:

a reactor chamber;

an electrostatic chuck for supporting a workpiece inside said chamber; and

at least one semiconductor grounding pin extending through said electrostatic chuck toward a plane whereon said chuck is capable of supporting said workpiece, said pin being movable between an extended position at which said pins can contact said workpiece and a retracted position.

25. The reactor of Claim 24 further comprising a frame supporting said pin, said frame being connectable to a ground potential.

26. The reactor of Claim 25 further comprising an actuator for moving said frame whereby to transport said pin between said extended and retracted positions.

27. The reactor of Claim 24 wherein said pin comprises silicon.

28. The reactor of Claim 24 wherein said pin comprises silicon carbide.

29. The reactor of Claim 24 further comprising a dielectric layer overlying said electrostatic chuck for insulating said workpiece from said chuck.

30. The reactor of Claim 29 wherein said electrostatic chuck is alternately connectable to a ground potential and to a voltage source and wherein said semiconductor pin is connected to a ground potential.

31. The reactor of Claim 24 further comprising a semiconductor collar around a periphery of said electrostatic chuck.

32. The reactor of Claim 31 wherein said semiconductor collar comprises silicon carbide.

33. The reactor of Claim 31 further comprising a heated semiconductor ring surrounding said electrostatic chuck.

34. A plasma reactor comprising:

a chamber;

a workpiece chuck for supporting a workpiece inside said chamber;

an RF power applicator and gas inlet apparatus for admitting a process gas into said chamber;

a semiconductor ring surrounding said workpiece chuck and heating apparatus for heating said semiconductor ring; and

a slit in said semiconductor ring for permitting thermal expansion of said semiconductor ring.

35. The plasma reactor of Claim 34 wherein said semiconductor ring comprises one of (a) silicon carbide and (b) silicon.

36. The plasma reactor of Claim 34 wherein said heating apparatus comprises plural radiant heat lamps underlying said semiconductor ring.

37. A plasma reactor comprising:

a chamber;

an electrostatic chuck for supporting a workpiece inside said chamber;

an RF power applicator and gas inlet apparatus for admitting a process gas into said chamber; and

a semiconductor collar at a periphery of said electrostatic chuck, semiconductor collar formed by chemical vapor deposition.

38. The reactor of Claim 37 wherein said semiconductor collar comprises silicon carbide.

39. A plasma reactor comprising:

a chamber;

an electrostatic chuck for supporting a workpiece inside said chamber;

an RF power applicator and process gas inlet apparatus; and

a silicon carbide collar at a periphery of said electrostatic chuck.

40. The plasma reactor of Claim 39 further comprising a semiconductor ring surrounding said electrostatic chuck and said silicon carbide collar.

41. A plasma reactor comprising:

a chamber including a ceiling;

a pedestal for supporting a workpiece inside said chamber;

process gas inlet apparatus;

an inductive antenna comprising plural stacked coil windings, each of said coil windings residing generally in a respective one of plural parallel planes, the windings in adjacent planes being connected at a step region common to all said planes wherein each winding transitions from one plane to the next plane, said coil windings being formed of a single conductor having a pair of connection sections, a first one of said connection sections extending from a top-most one of said windings and a second one of said ends extending from a bottom-most one of said windings, said first connection section extending upwardly away from said top-most winding, said second connection section following an arcuate path upwardly from said bottom-most winding to said top-most winding so as to provide an effective number of stacked windings which is generally uniform along said step region.

42. The plasma reactor of Claim 41 wherein said arcuate path is such that said second connection section is most nearly parallel to said parallel planes near said bottom-most winding and is most nearly perpendicular to said parallel planes near said top-most winding.

43. A plasma reactor comprising:

a chamber including a ceiling;

a pedestal for supporting a workpiece inside said chamber;

process gas inlet apparatus;

an inductive antenna comprising plural stacked coil windings, each of said coil windings residing generally in a respective one of plural parallel planes, the windings in adjacent planes being connected at a step region common to all said planes wherein each winding transitions from one plane to the next plane, said antenna further comprising a conductor coupled to a bottom-most one of said windings extending upwardly from one azimuthal end of said step region to the other azimuthal end of said step region toward the plane of a top-most one of said windings.

44. The reactor of Claim 43 wherein said upwardly extending conductor follows an upwardly curving arcuate path.

FIG. 1

FIG. 2

FIG. 3A

FIG. 3B

FIG. 3C

FIG. 3D

FIG. 3E
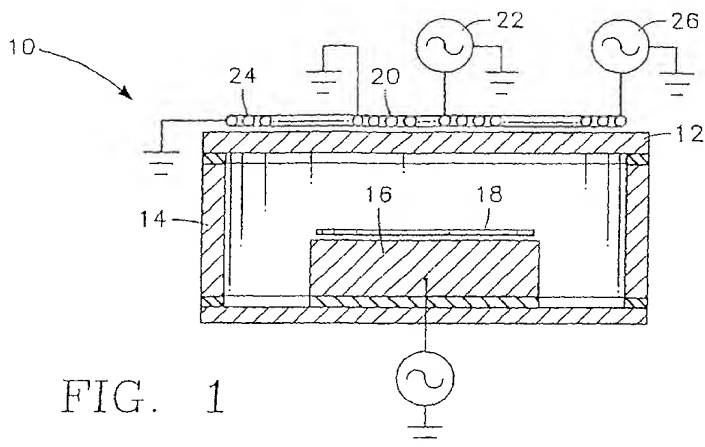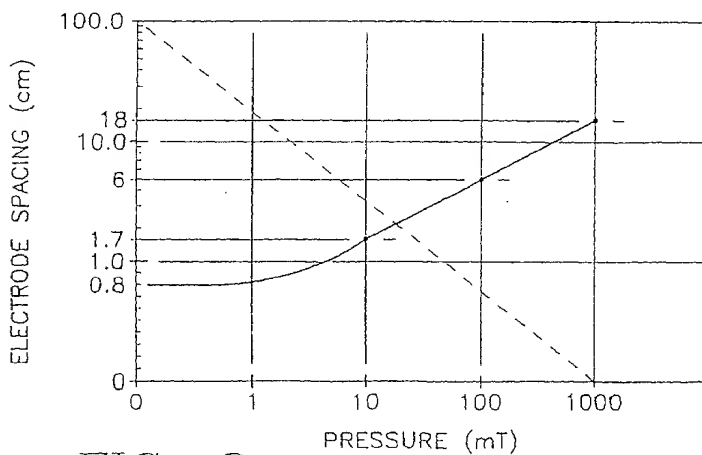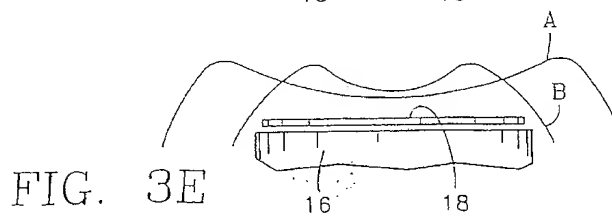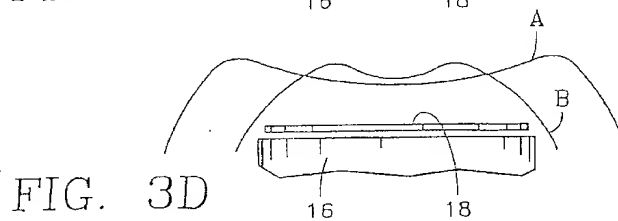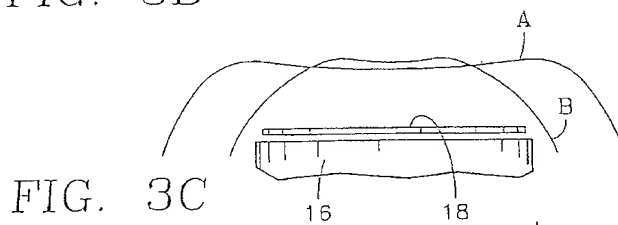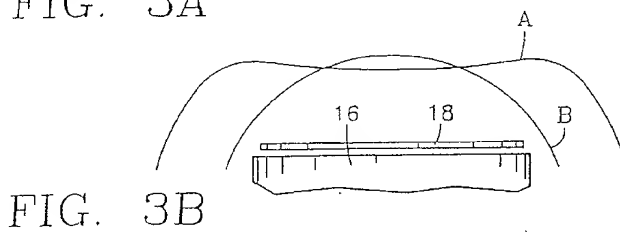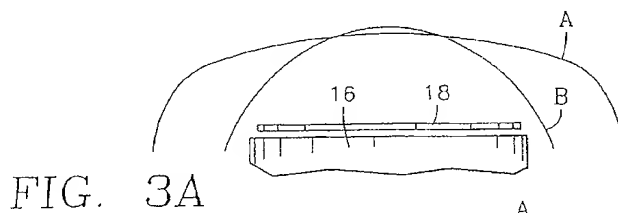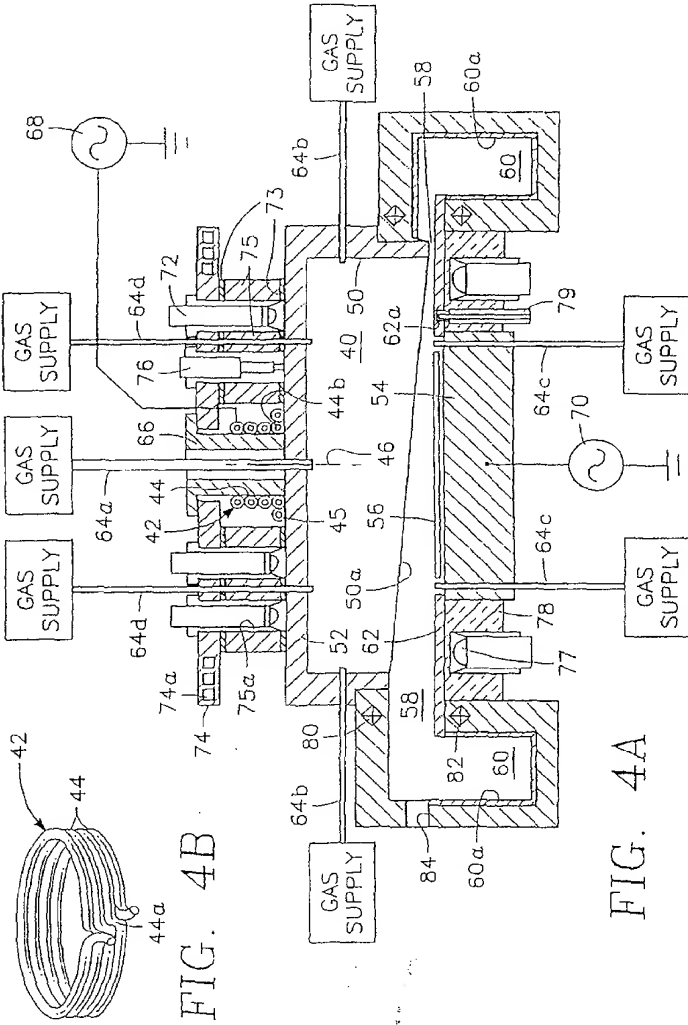
FIG. 4B

FIG. 4A

FIG. 4C

FIG. 4D

FIG. 4E

FIG. 5

FIG. 6

FIG. 7C

FIG. 7B

FIG. 7A

FIG. 8
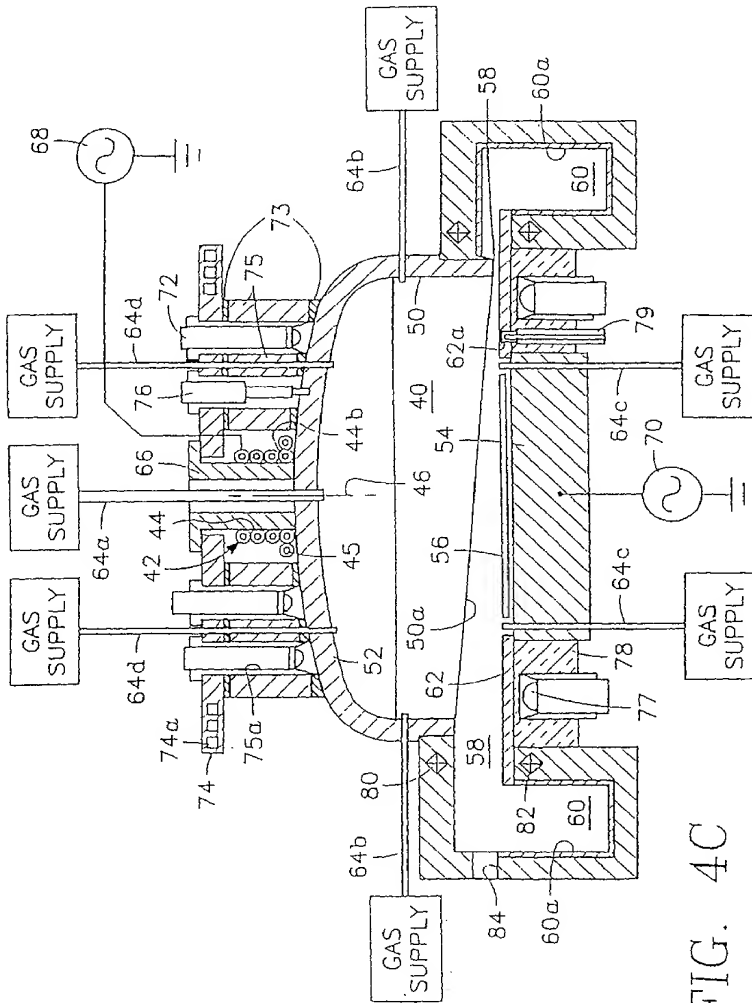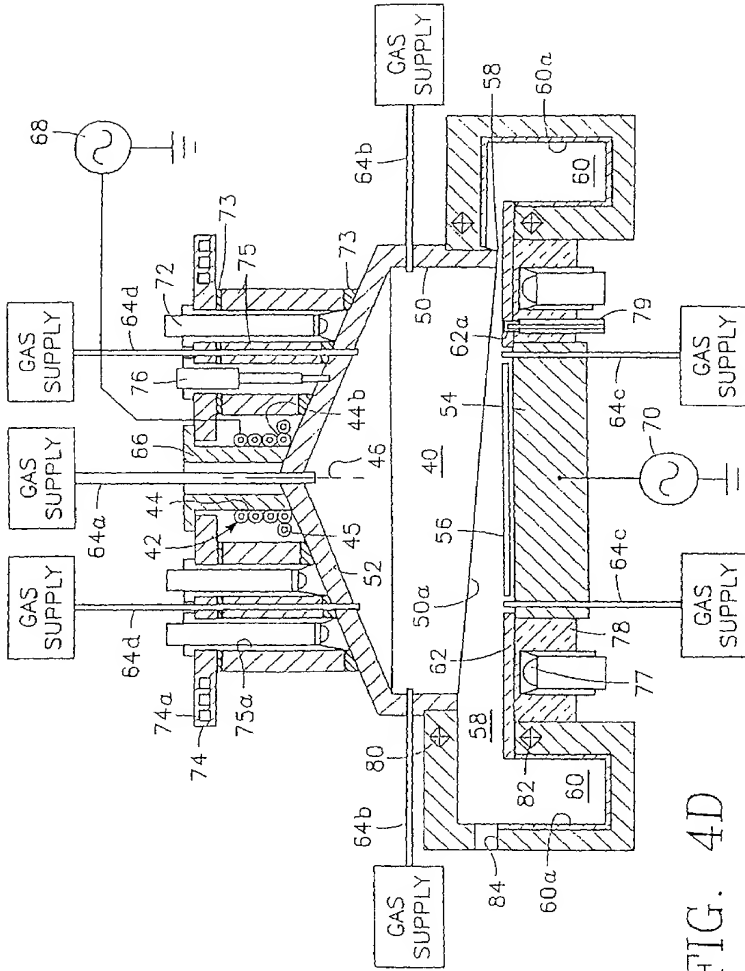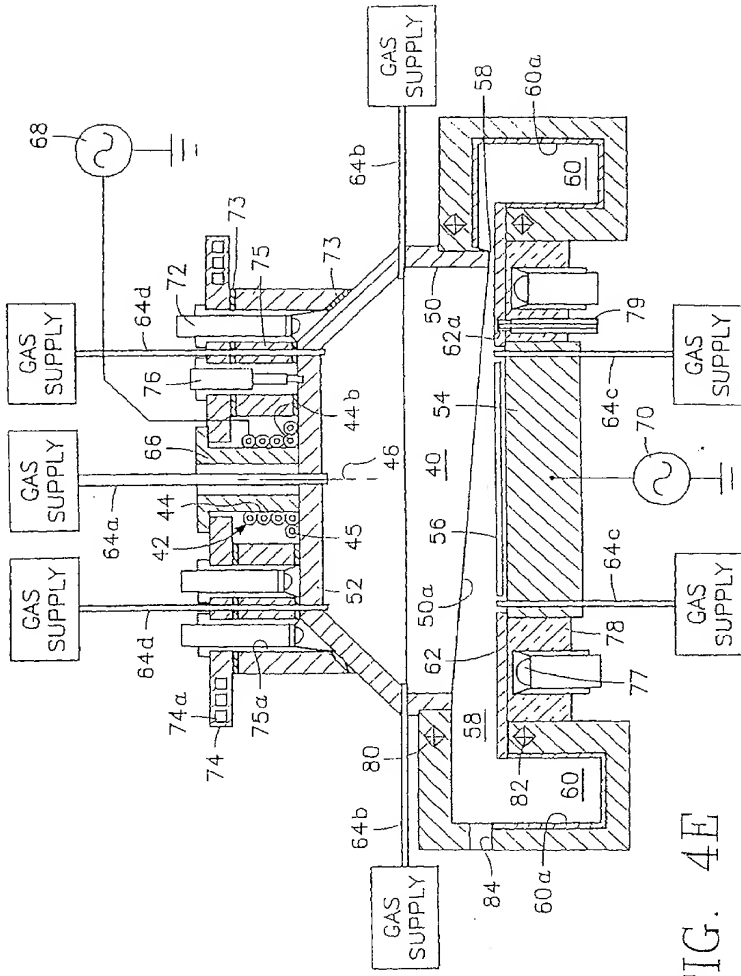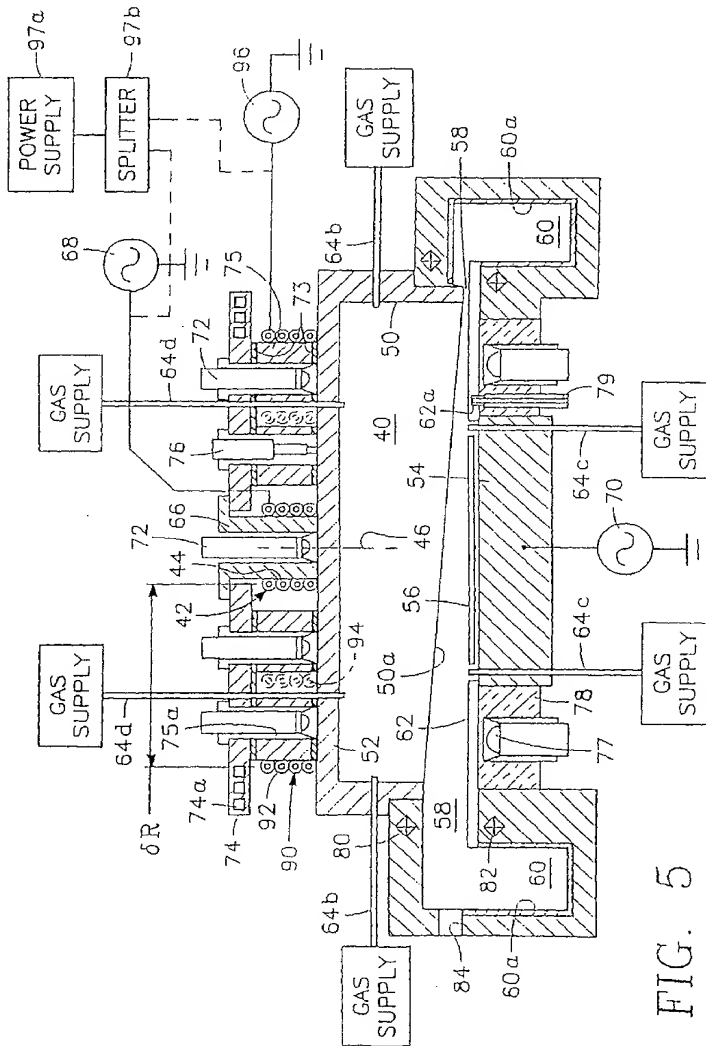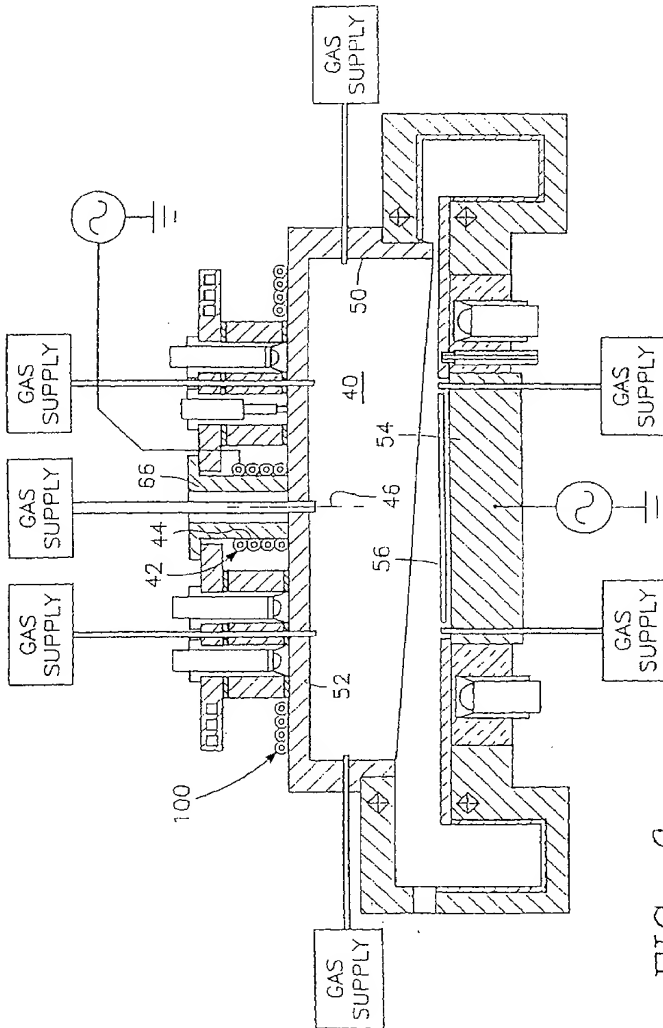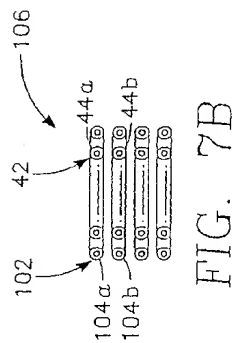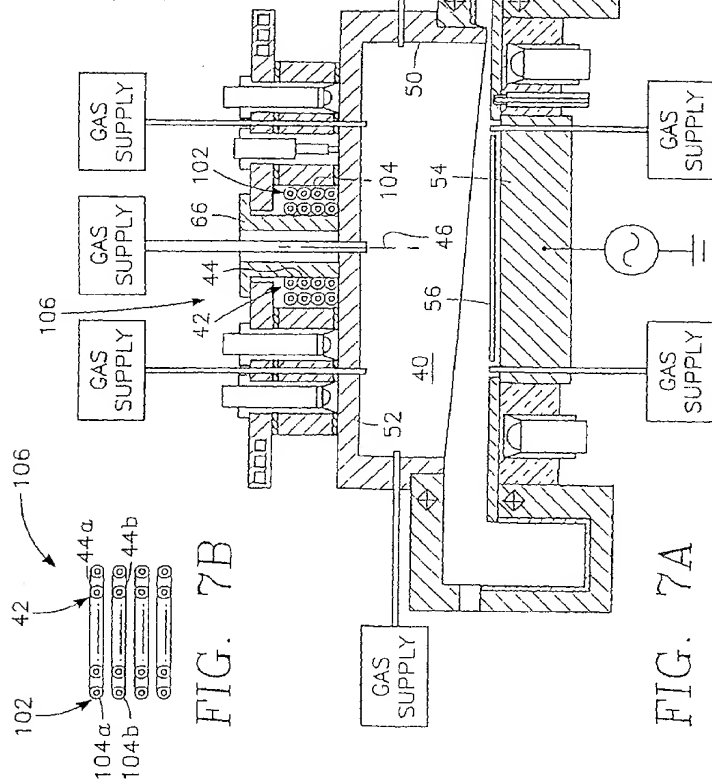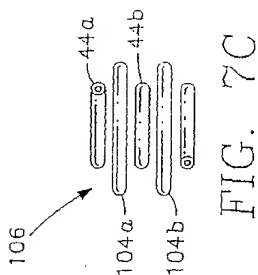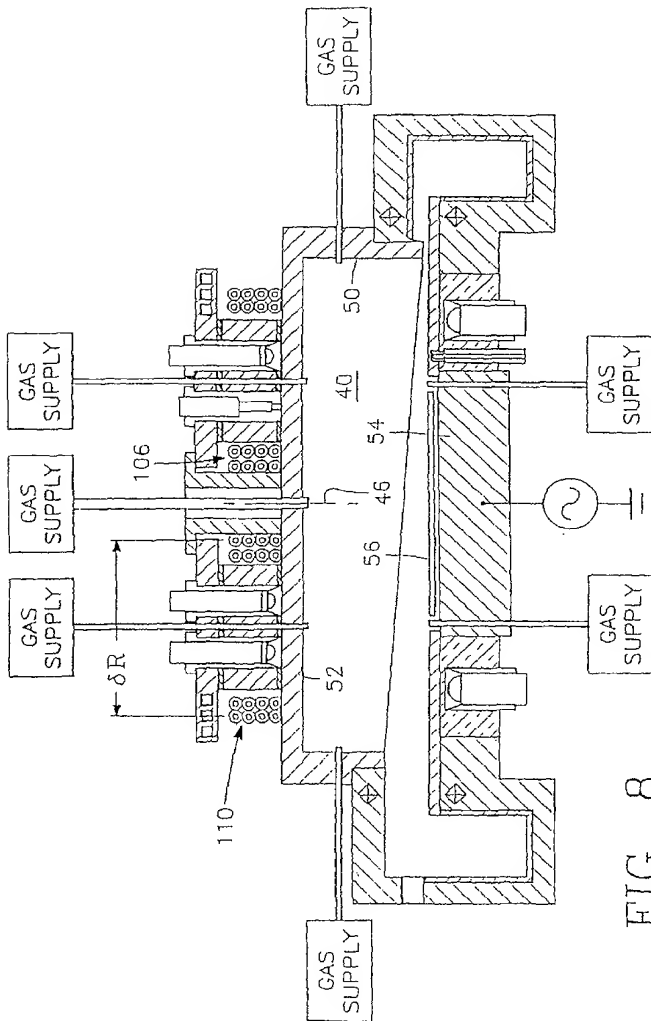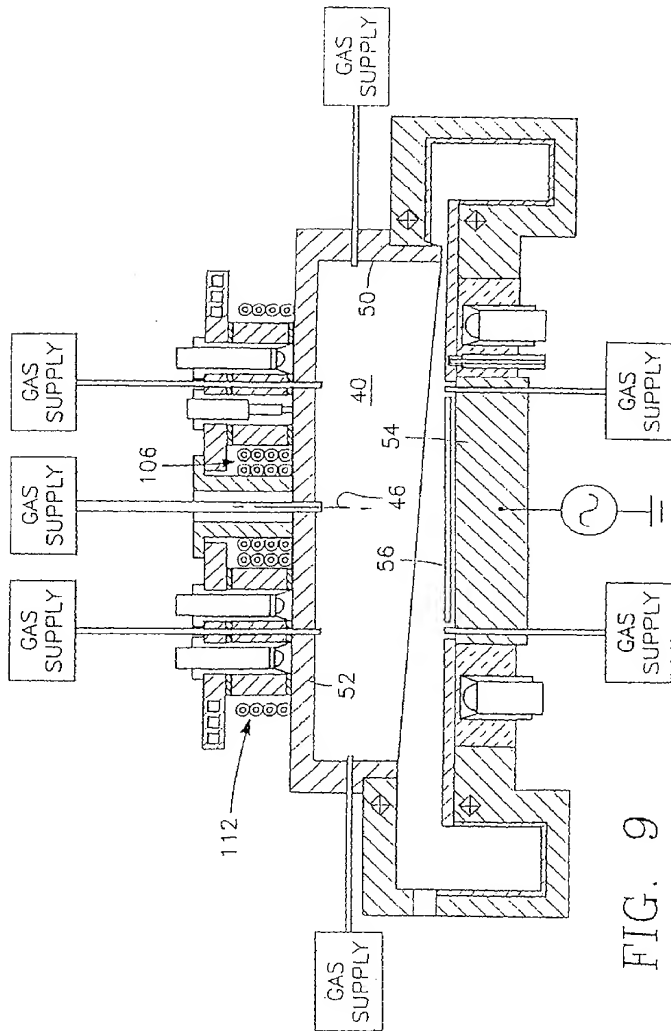
FIG. 9
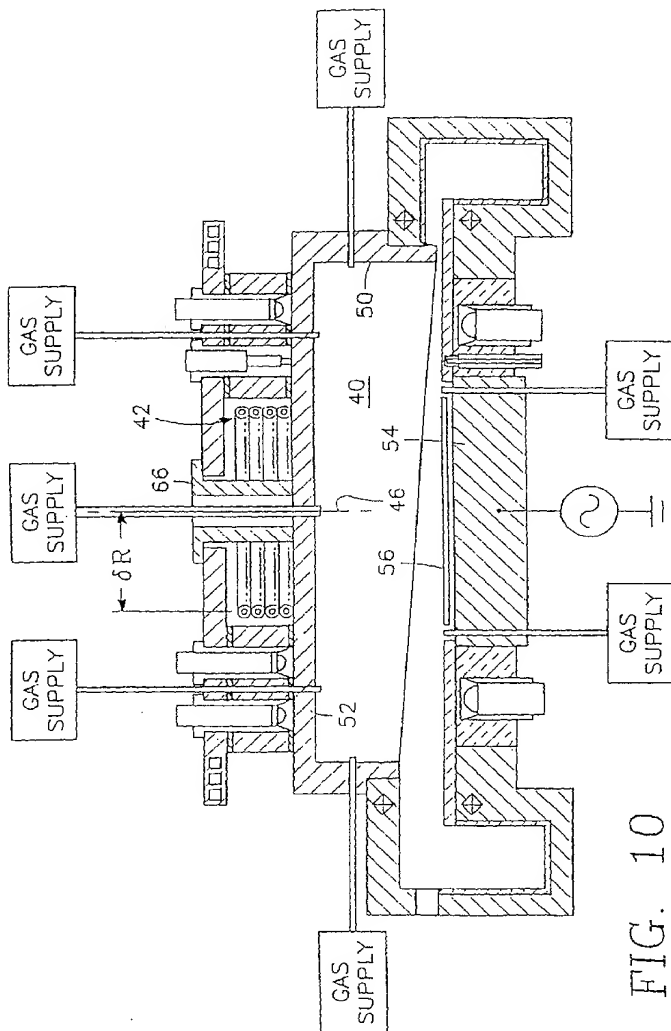
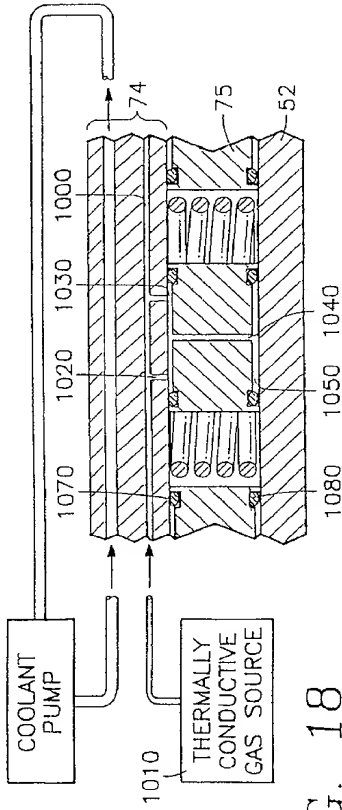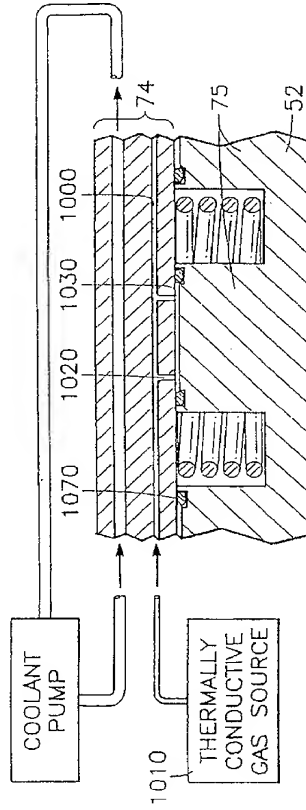FIG. 10
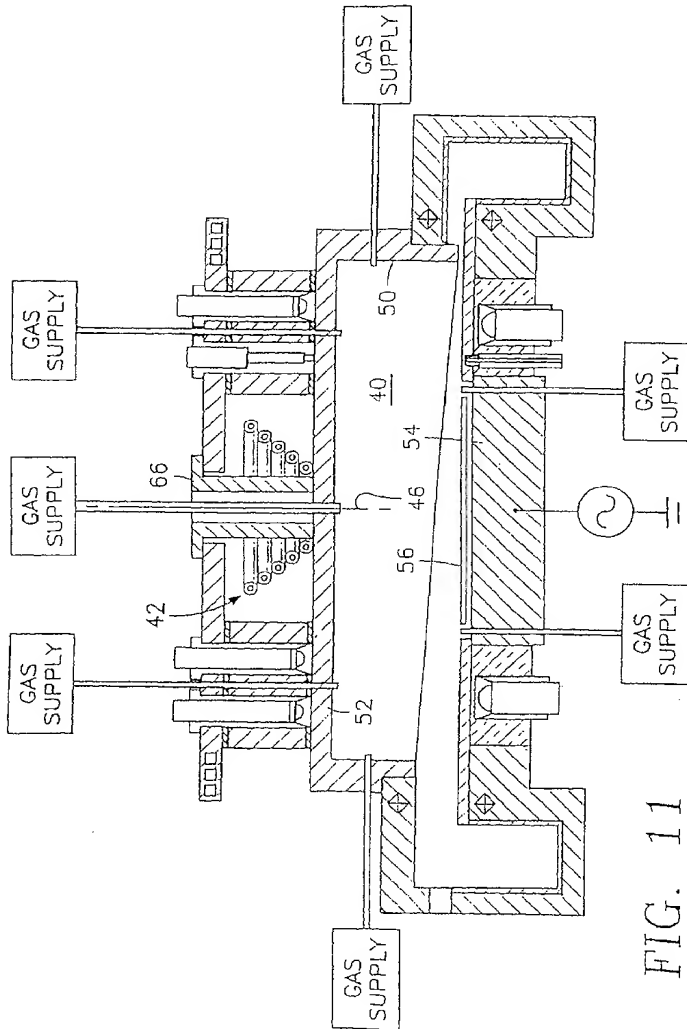
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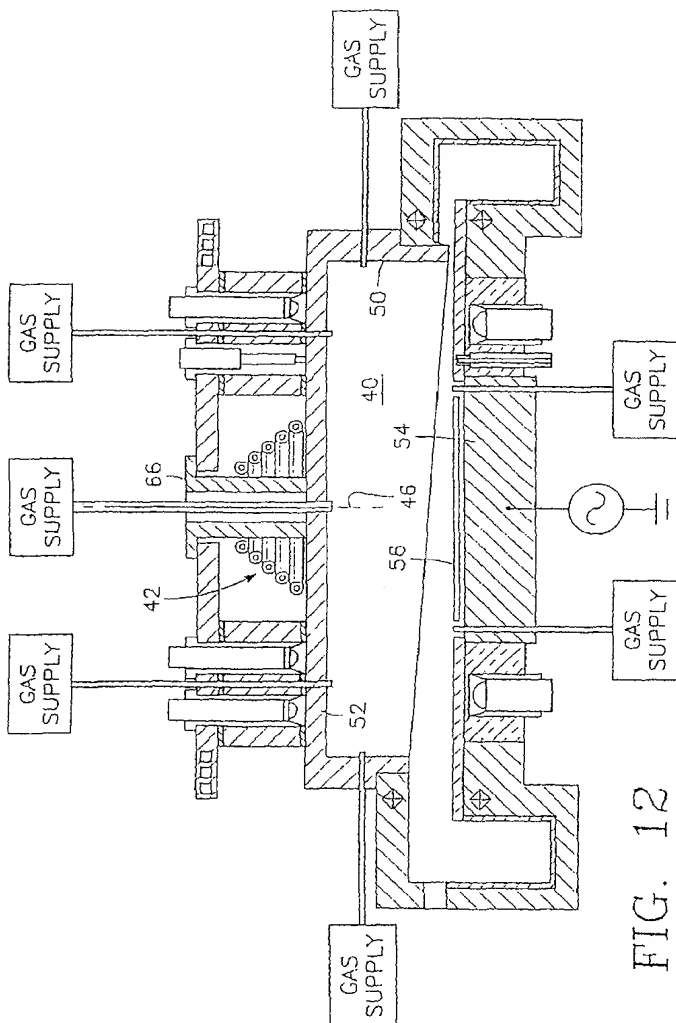
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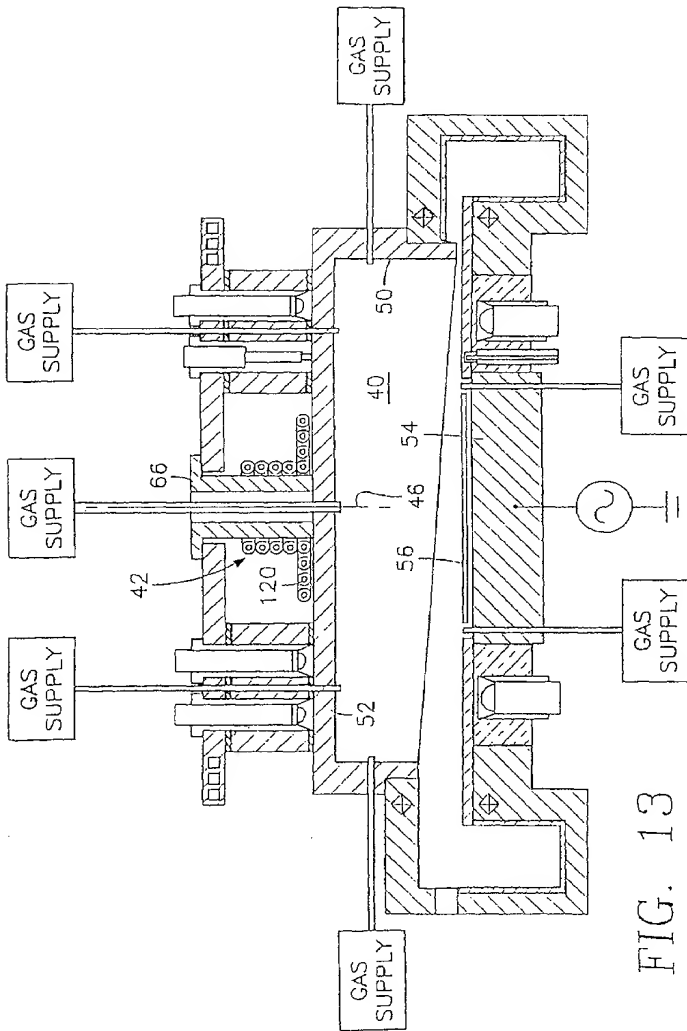
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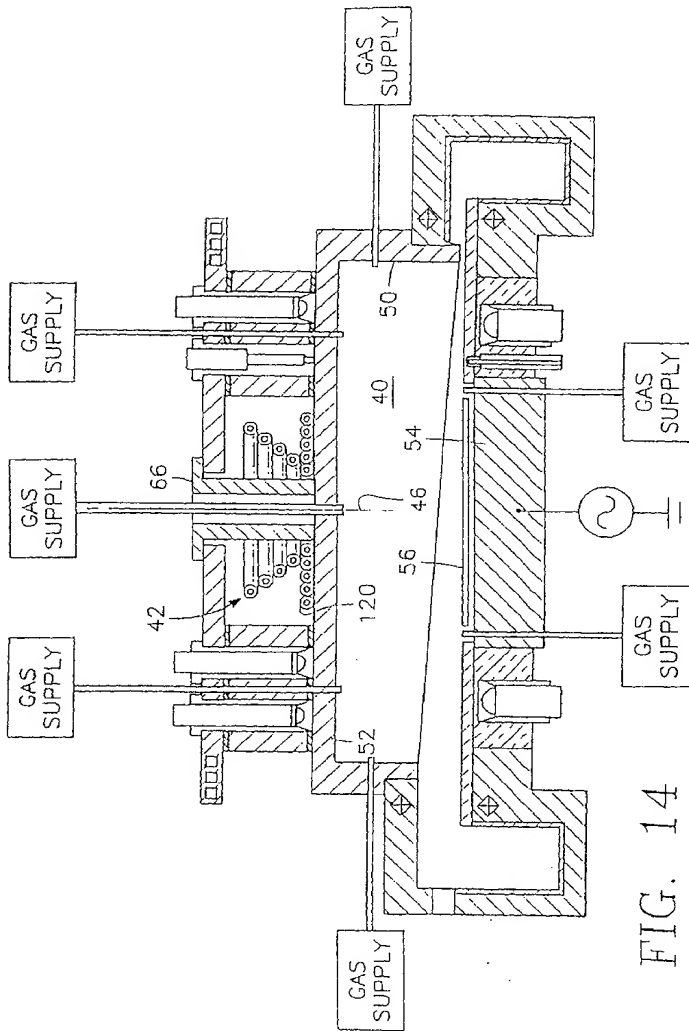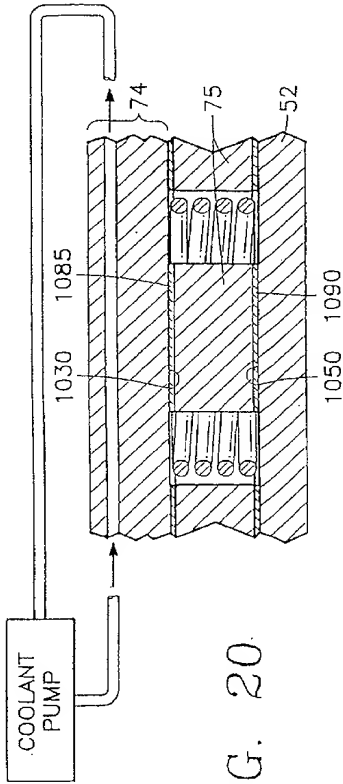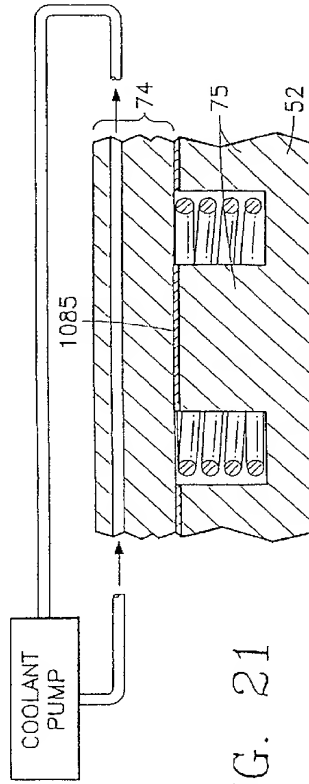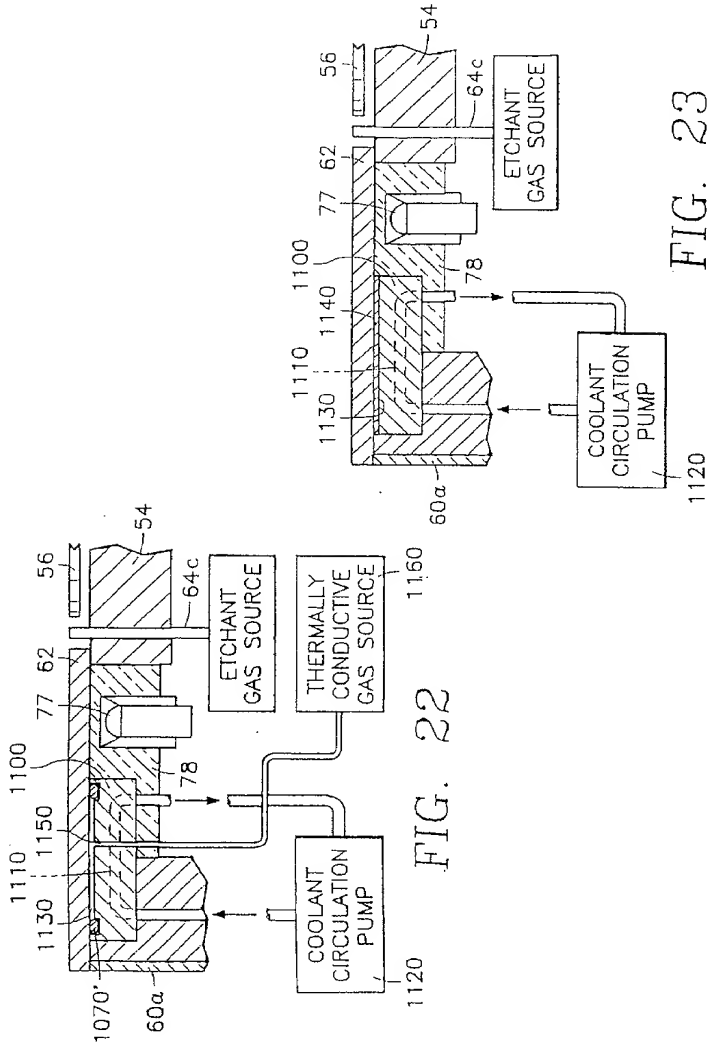
FIG. 14
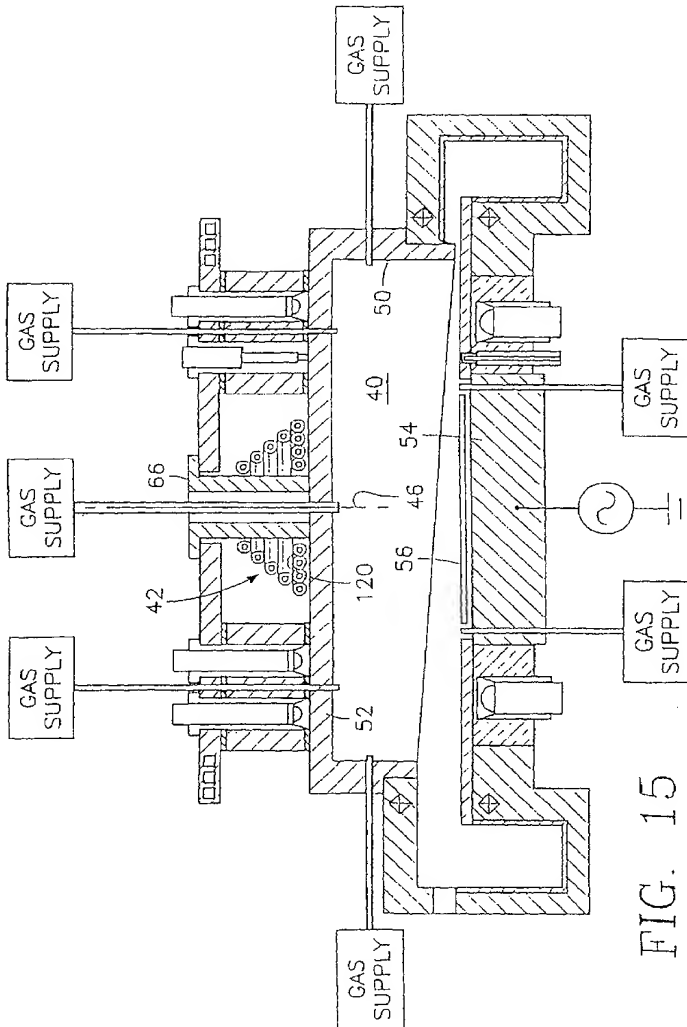
FIG. 15
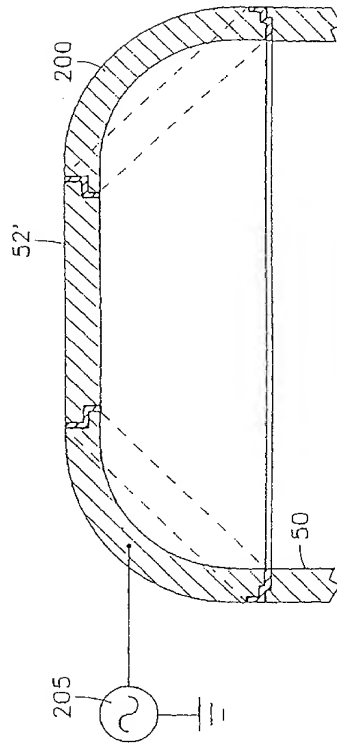
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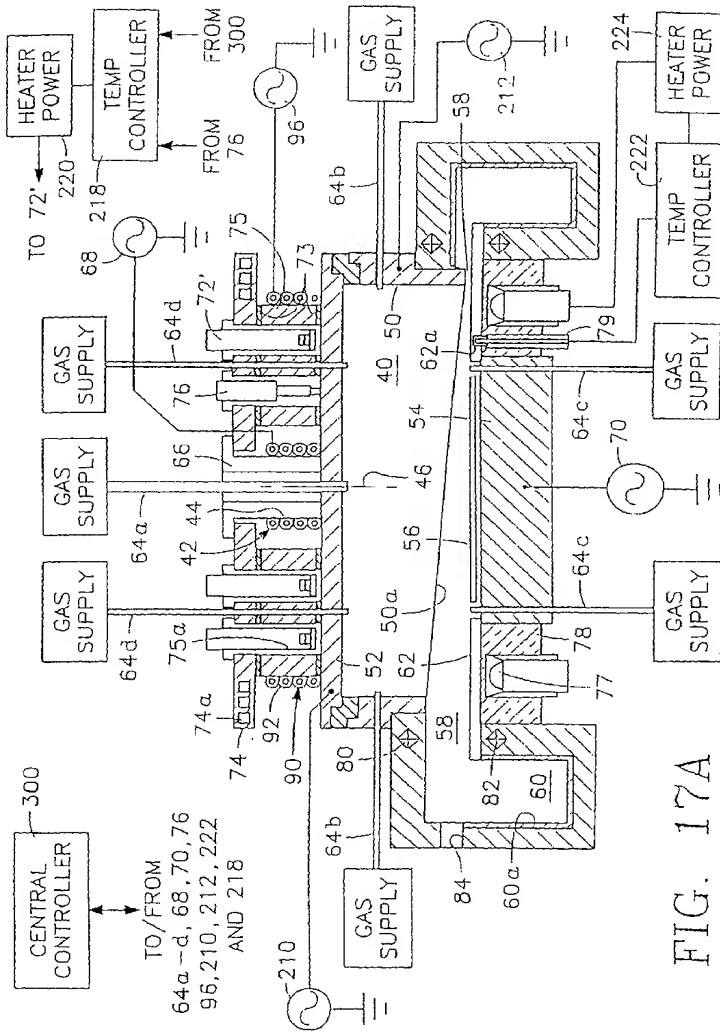
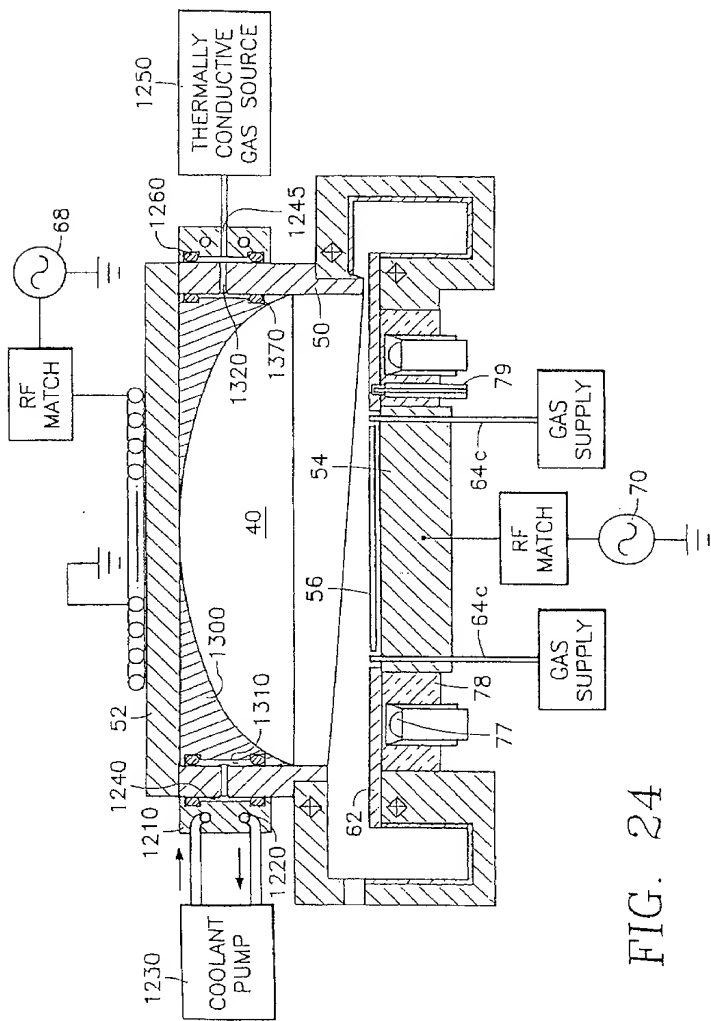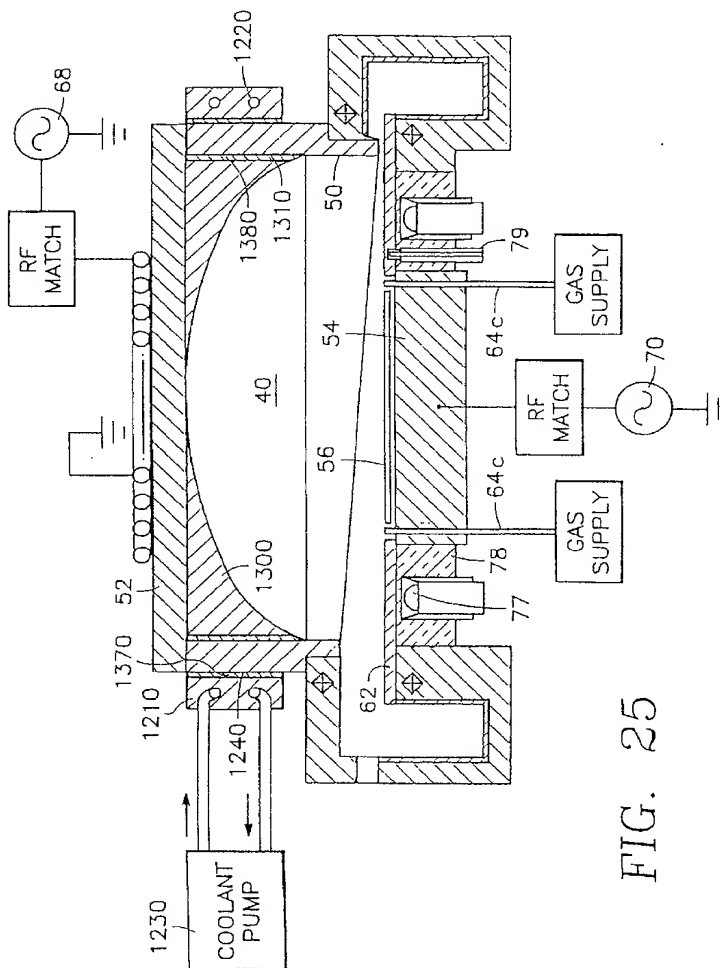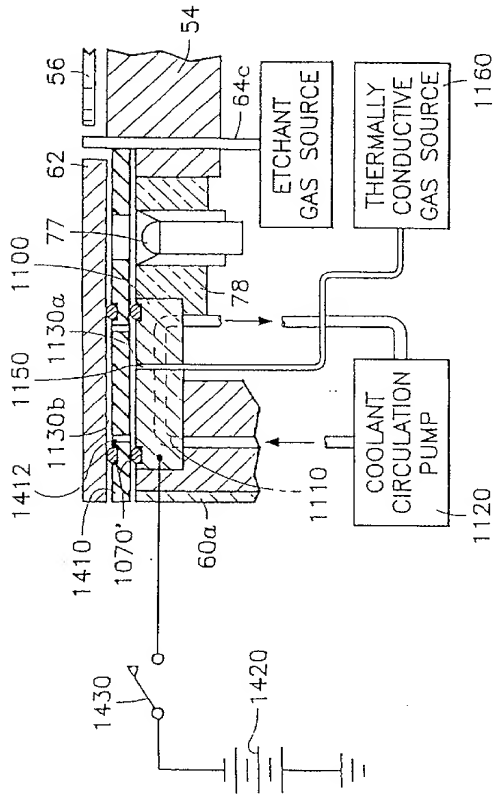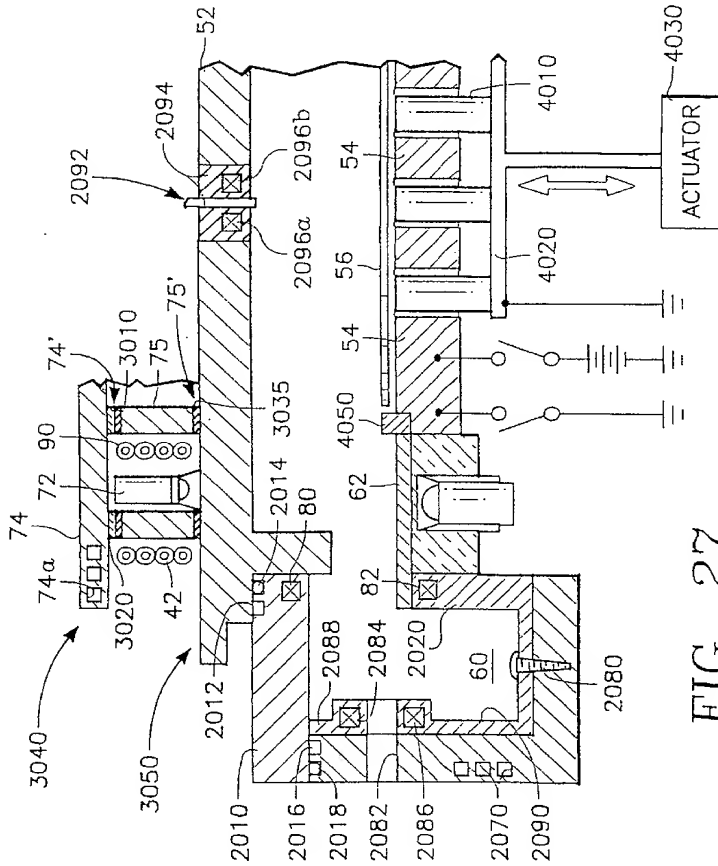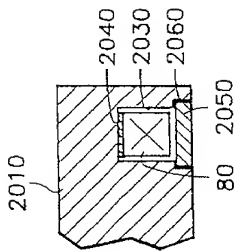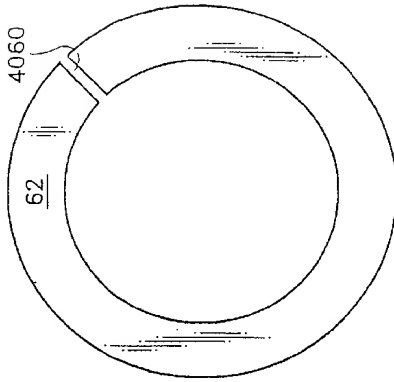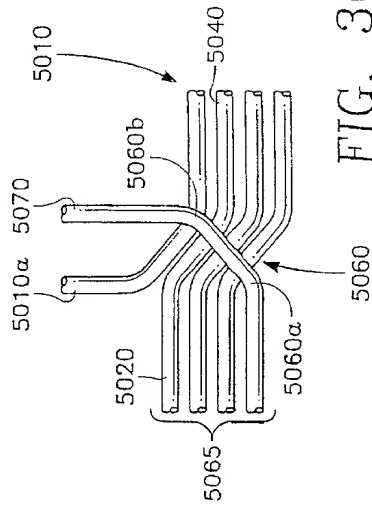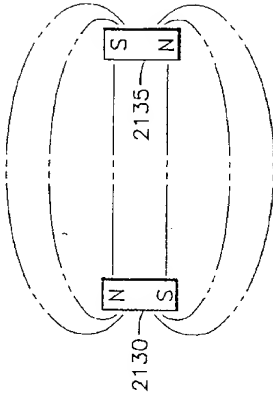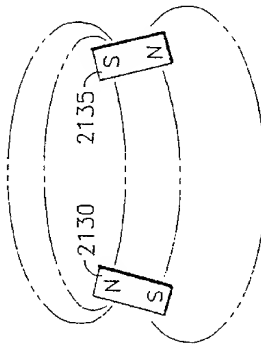FIG. 17A
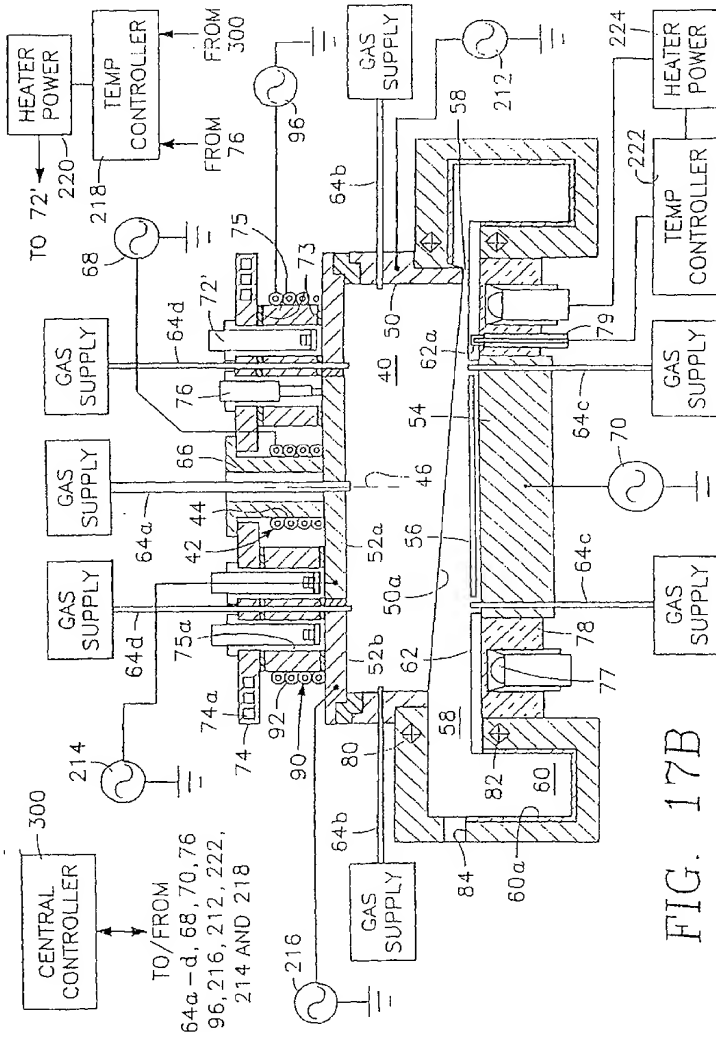
FIG. 17B

FIG. 18

FIG. 19

FIG. 20

FIG. 21

FIG. 23

FIG. 22

FIG. 24

FIG. 25

FIG. 26

FIG. 27

FIG. 29

62

4060

FIG. 28

2010

2040
2030
2060

2050
80

FIG. 30

5010

5010a 5070

5060b

5040

5060

5060a

5020

5065

FIG. 31B

FIG. 31E

FIG. 31A

FIG. 31D

FIG. 31C

2130

2135